

THE
SCIENTIFIC PAPERS
OF
SIR WILLIAM HUGGINS

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PUBLICATIONS
OF
SIR WILLIAM HUGGINS'S OBSERVATORY
VOL. I.

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 AN ATLAS OF
REPRESENTATIVE
STELLAR SPECTRA
FROM λ 4870 TO λ 3300

TOGETHER WITH
A DISCUSSION OF THE EVOLUTONAL ORDER
OF THE STARS, AND THE INTERPRETATION
OF THEIR SPECTRA

BY
SIR WILLIAM HUGGINS, K.C.B., O.M.
AND
LADY HUGGINS

LONDON
WILLIAM WESLEY AND SON
28 ESSEX STREET, STRAND
1899

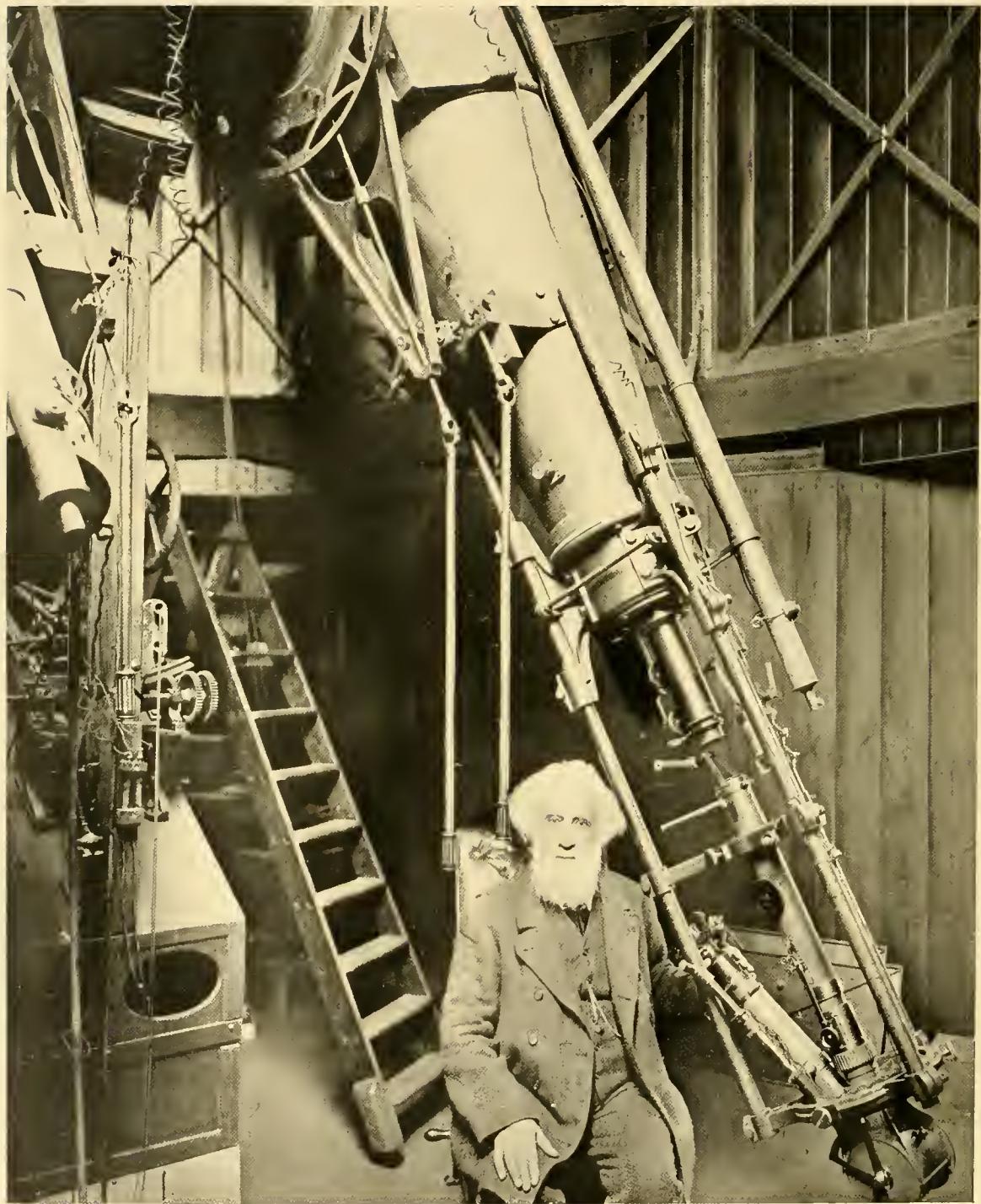
PUBLICATIONS
OF
SIR WILLIAM HUGGINS'S OBSERVATORY

VOL. II



VIEW OF THE OBSERVATORY

1909



INTERIOR OF THE OBSERVATORY

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THE SCIENTIFIC PAPERS

OF

SIR WILLIAM HUGGINS, K.C.B., O.M.

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WITH SIXTY-SIX ILLUSTRATIONS

LONDON
28 ESSEX STREET, STRAND
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1909

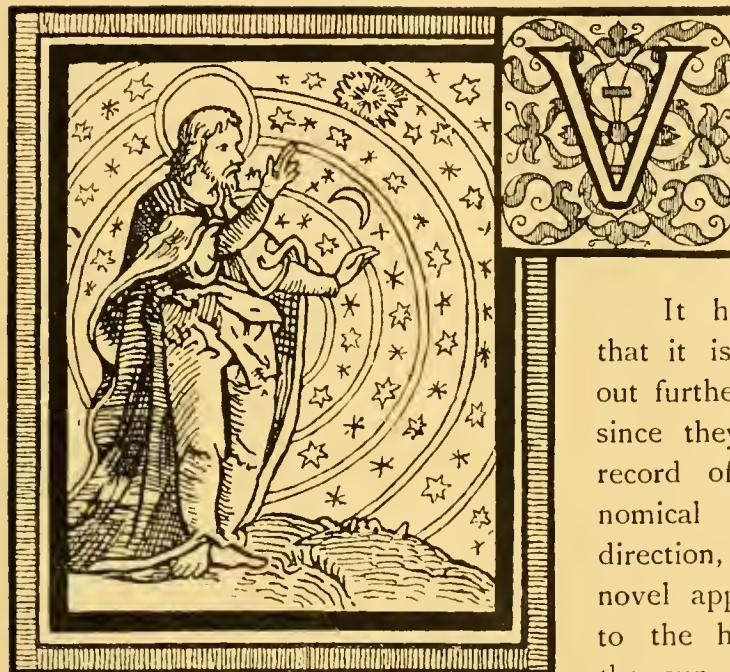


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PREFACE



OLUME II. of the Publications of this Observatory contains a reprint of the published Papers on the work done in the Observatory since its foundation by me in 1856.

It has been represented to us that it is desirable to reprint, without further delay, these early Papers, since they contain the contemporary record of a development of astronomical work in an entirely new direction, through the, at that time, novel application of the Spectroscope to the heavenly bodies other than the sun.

These original observations, notwithstanding the serious drawbacks and limitations which must be present in pioneering work, will have in their collected form, we are told, all the interest of a nascent science, since they led directly to, and indeed themselves formed a not inconsiderable part of the foundations of, a new branch of Astronomy, which extends the chemistry and physics of the earth to the heavenly bodies, and under the new name of Astrophysics, is to-day zealously cultivated in all the principal observatories of the world.

Looking back, with the knowledge of the more efficient and perfectly adapted instruments and methods of work which have been gradually introduced during the last forty years, no one can be more conscious than I am of the inevitable shortcomings of my pioneer instruments and methods of work, which had to be created under circumstances of no little difficulty. These shortcomings

The picture part of the initial is from the *Coverdale Bible*, A.D. 1535. The letter is taken from the *First English Prayer Book*, 1549.

prevented the attainment of accurate results in some single cases, but time has shown that they did not affect the fundamental general correctness of my early work.

There are obviously two principal orders of arrangement under which the Papers might be placed. One plan would be to print the Papers strictly in the order of their dates; in this case, Papers on different subjects would follow each other. The other plan would be to make a primary arrangement under subjects, leaving the papers of each subject-division to follow in the order of their dates of publication. Under this arrangement, in a few cases, it would be necessary to divide up a Paper, placing the separate parts of the same Paper under different subjects.

It appears to us that the plan of arrangement under subjects possesses direct advantages sufficiently great to more than overbalance the occasional dividing up of a Paper. The student will be able to find easily, and at once, the information which he is seeking, and it will be no little convenience to him to have all the observations on one subject made at the Observatory, brought together in one place, in the order of date.

This plan has been adopted, taking as a rule, for the divisional subjects, the different classes of the heavenly bodies.

We have decided, after some consideration, to reprint all the Papers, as they appeared, in full, without alteration or omission. In some cases, where it appeared to us to be desirable, short notes have been added.

It may be well to remind the reader that this volume requires for its completion, Volume I., *ATLAS OF REPRESENTATIVE STELLAR SPECTRA*, published in 1899. The Atlas contains the later original work of the Observatory, which had not been previously published elsewhere; and, in addition, it offers theoretical discussions on this newer work in connection with the earlier observations contained in the separate Papers reprinted in the present volume.

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Hon. John C. Breckinridge

1860-1865



Photo by Reginald Haines

From *Great Living Portraits*

Section I
OBSERVATORY AND INSTRUMENTS

LIST OF PAPERS

- “ Description of an Observatory erected at Upper Tulse Hill.”
Month. Not., vol. xvi., p. 175, 1856. P. 5.
- “ On the Spectra of some of the Fixed Stars” (and Dr. Millar).
Phil. Trans., vol. cliv., pp. 415–417, 1864. P. 8.
- “ On the Photographic Spectra of Stars.”
Phil. Trans., vol. clxxi., p. 669, 1880. P. 12.
- “Atlas of Representative Spectra,” Wesley & Son, 1899.
Description of Spectroscopes, c. iv., p. 43.
- “The Tulse Hill Spectroscope.”
Astron. and Astrophys., Sept. 1893, p. 117. P. 16.
- “The Tulse Hill Ultra-violet Spectroscope.”
Astrophys. Journ., vol. i., p. 359, 1895. P. 21.
- “On an Automatic Arrangement for giving Breadth to Stellar Spectra on the Photographic Plate.”
Astrophys. Journ., vol. v., p. 8, 1897. P. 26.
- “Description of a Hand Spectrum-Telescope.”
Proc. Roy. Soc., vol. xvi., p. 241, 1868. P. 28.
- “On a Registering Spectroscope.”
Proc. Roy. Soc., vol. xix., p. 317, 1871. P. 31

HISTORICAL STATEMENT

(From *The Nineteenth Century Review*, June 1897)

IN 1856 I built a convenient observatory opening by a passage from the house, and raised so as to command an uninterrupted view of the sky except on the north side. It consisted of a dome 12 feet in diameter, and a transit room.* There was erected in it an equatorially mounted telescope by Dollond of 5 inches aperture, at that time looked upon as a large rather than a small instrument. I commenced work on the usual lines, taking transits, observing and making drawings of planets. Some of Jupiter now lying before me, I venture to think, would not compare unfavourably with drawings made with the larger instruments of the present day.

About that time Mr. Alvan Clark, the founder of the American firm famous for the construction of the great object-glasses of the Lick and the Yerkes Observatories, then a portrait-painter by profession, began, as an amateur, to make object-glasses of large size for that time, and of very great merit. Specimens of his earliest work came into the hands of my friend Mr. Dawes, and received the high approval of that distinguished judge. In 1858 I purchased from Mr. Dawes an object-glass by Alvan Clark of 8 inches diameter, which he parted with to make room for a lens of a larger diameter by a quarter of an inch, which Mr. Clark had undertaken to make for him. I paid the price that it had cost Mr. Dawes—namely, £200. This telescope was mounted for me equatorially and provided with a clock motion by Mr. Cooke of York.

I soon became a little dissatisfied with the routine character of ordinary astronomical work, and in a vague way sought about in my mind for the possibility of research upon the heavens in a new direction or by new methods. It was just at this time, when a vague longing after newer methods of observation for attacking many of the problems of the heavenly bodies filled my mind, that the news reached me of Kirchhoff's great discovery of the true nature and the chemical constitution of the sun from his interpretation of the Fraunhofer lines.

* See *Month. Not. R. Ast. S.*, vol. xvi., p. 175.

This news was to me like the coming upon a spring of water in a dry and thirsty land. Here at last presented itself the very order of work for which in an indefinite way I was looking—namely, to extend his novel methods of research upon the sun to the other heavenly bodies. A feeling as of inspiration seized me: I felt as if I had it now in my power to lift a veil which had never before been lifted; as if a key had been put into my hands which would unlock a door which had been regarded as for ever closed to man—the veil and door behind which lay the unknown mystery of the true nature of the heavenly bodies. This was especially work for which I was to a great extent prepared, from being already familiar with the chief methods of chemical and physical research.

It was just at this time that I happened to meet at a soirée of the Pharmaceutical Society, where spectrosopes were shown, my friend and neighbour, Dr. W. Allen Miller, Professor of Chemistry at King's College, who had already worked much on chemical spectroscopy. A sudden impulse seized me to suggest to him that we should return home together. On our way home I told him of what was in my mind, and asked him to join me in the attempt I was about to make, to apply Kirchhoff's methods to the stars. At first, from considerations of the great relative faintness of the stars, and the great delicacy of the work from the earth's motion, even with the aid of a clockwork, he hesitated as to the probability of our success. Finally he agreed to come to my observatory on the first fine evening, for some preliminary experiments as to what we might expect to do upon the stars.

At that time a star spectroscope was an instrument unknown to the optician. I remember that for our first trials we had one of the hollow prisms filled with bisulphide of carbon so much in use then, and which in consequence of a small leak smelt abominably. To this day this pungent odour reminds me of star spectra!

Let us look at the problem which lay before us. It is difficult for any one, who has now only to give an order for a star spectroscope, to understand in any true degree the difficulties which we met with in attempting to make such observations for the first time. From the sun with which the Heidelberg professors had to do—which, even bright as it is, for some parts of the spectrum has no light to spare—to the brightest stars is a very far cry. The light received at the earth from a first magnitude star, as Vega, is only about the one forty thousand millionth part of that received from the sun.

Fortunately, as the stars are too far off to show a true disk, it is possible to concentrate all the light received from the star upon a large mirror or object-glass, into the telescopic image, and so increase its brightness.

We could not make use of the easy method adopted by Fraunhofer of placing a prism before the object-glass, for we needed a terrestrial spectrum,

taken under the same conditions, for the interpretation, by a simultaneous comparison with it of the star's spectrum. Kirchhoff's method required that the image of a star should be thrown upon a narrow slit simultaneously with the light from a flame or from an electric spark.

These conditions made it necessary to attach a spectroscope to the eye end of the telescope, so that it would be carried with it, with its slit in the focal plane. Then, by means of a small reflecting prism placed before one half of the slit, light from a terrestrial source at the side of the telescope could be sent into the instrument together with the star's light, and so form a spectrum by the side of the stellar spectrum, for convenient comparison with it.

This was not all. As the telescopic image of a star is a point, its spectrum will be a narrow line of light without appreciable breadth. Now for the observation either of dark or of bright lines across the spectrum a certain breadth is absolutely needful. To get breadth, the pointlike image of the star must be broadened out.

As light is of first importance, it was desirable to broaden the star's image only in the one direction necessary to give breadth to the spectrum; or, in other words, to convert the stellar point into a short line of light. Such an enlargement in one direction only could be given by the device, first employed by Fraunhofer himself, of a lens convex or concave in one direction only, and flat, and so having no action on the light, in a direction at right angles to the former one.

When I went to the distinguished optician, Mr. Andrew Ross, to ask for such a lens, he told me that no such lenses were made in England, but that the spectacle lenses then very occasionally required to correct astigmatism—first used, I believe, by the then Astronomer Royal, the late Sir George Airy—were ground in Berlin. He procured for me from Germany several lenses; but not long after, a cylindrical lens was ground for me by Browning. By means of such a lens, placed within the focus of the telescope, in front of the slit, the pointlike image of a star could be widened in one direction so as to become a very fine line of light, just so long as, but no longer than, was necessary to give to the spectrum a breadth sufficient for distinguishing any lines by which it may be crossed.

It is scarcely possible at the present day, when all these points are as familiar as household words, for any astronomer to realise the large amount of time and labour which had to be devoted to the successful construction of the first star spectroscope. Especially was it difficult to provide for the satisfactory introduction of the light for the comparison spectrum. We soon found, to our dismay, how easily the comparison lines might become instrumentally shifted, and so be no longer strictly fiducial. As a test we used the solar lines as reflected

to us from the moon—a test of more than sufficient delicacy with the resolving power at our command.

Then it was that an astronomical observatory began, for the first time, to take on the appearance of a laboratory. Primary batteries, giving forth noxious gases, were arranged outside one of the windows; a large induction coil stood mounted on a stand on wheels so as to follow the positions of the eye end of the telescope, together with a battery of several Leyden jars; shelves with Bunsen burners, vacuum tubes, and bottles of chemicals, especially of specimens of pure metals, lined its walls.

In 1870 my observatory was enlarged from a dome of 12 feet in diameter to a drum having a diameter of 18 feet. This alteration had been made for the reception of a larger telescope made by Sir Howard Grubb, at the expense of a legacy to the Royal Society, and which was placed in my hands on loan by that society. This instrument was furnished with two telescopes: an achromatic of 15 inches aperture and a Cassegrain of 18 inches aperture, with mirrors of speculum metal. At this time one only of these telescopes could be in use at a time. Later on, in 1882, by a device which occurred to me of giving each telescope an independent declination axis, the one working within the other, both telescopes could remain together on the equatorial mounting, and be equally ready for use.

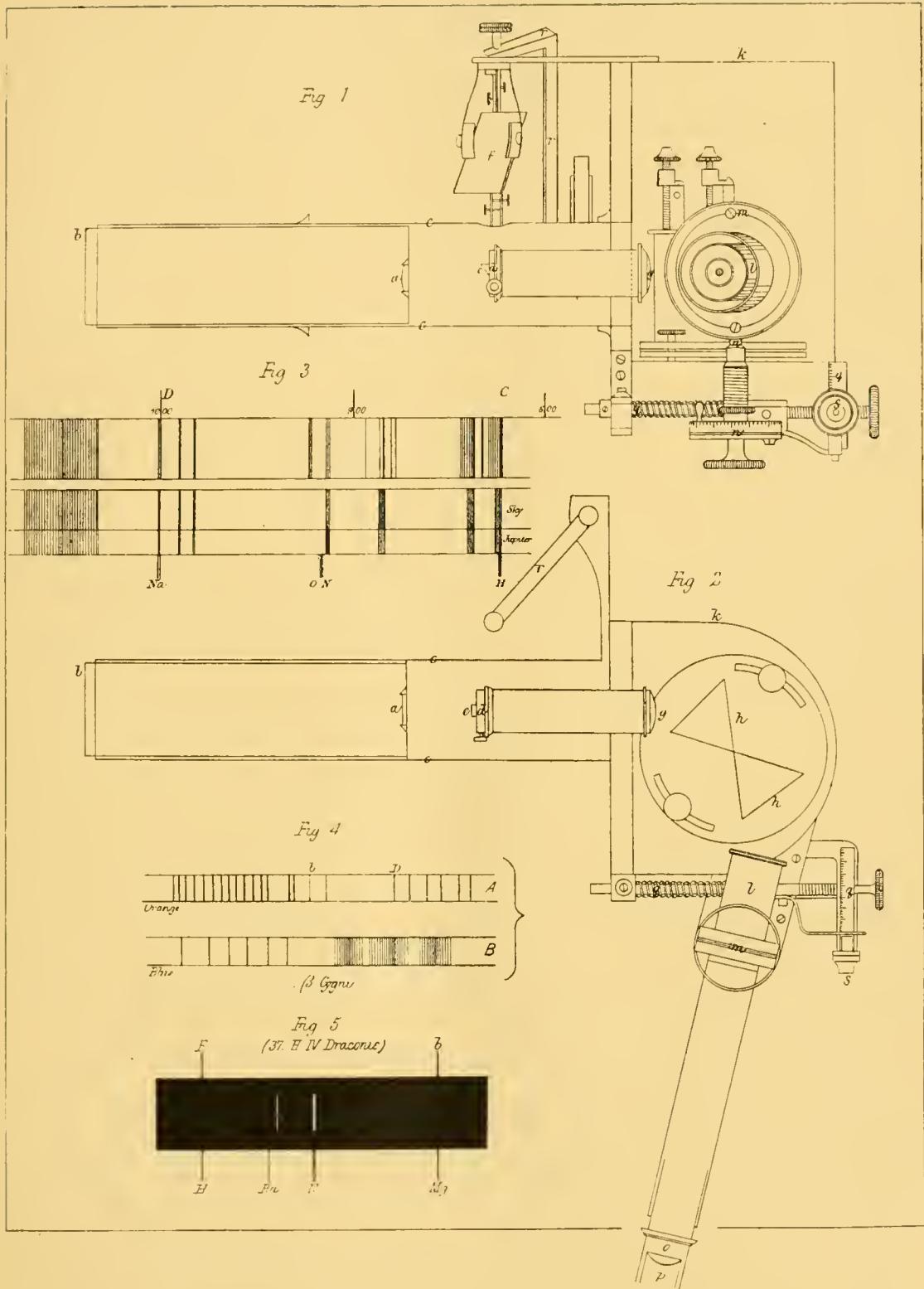
SPECTROSCOPIC INSTRUMENTS EMPLOYED IN MY OBSERVATIONS (CONJOINTLY WITH DR. W. ALLEN MILLER) ON THE SPECTRA OF THE STARS

(From the *Phil. Trans. R. S.*, vol. cliv., pp. 415-417, 1864)

DESCRIPTION OF THE APPARATUS AND METHODS OF OBSERVATION EMPLOYED

THIS specially constructed spectrum apparatus is attached to the eye end of a refracting telescope of 8 inches aperture and 10 feet focal length, which is mounted equatorially in the observatory of Mr. Huggins at Upper Tulse Hill. The object-glass is a very fine one, by Alvan Clark of Cambridge, Massachusetts; the equatorial mounting is by Cooke of York; and the telescope is carried very smoothly by a clock motion.

As the linear spectrum of the point of light which a star forms at the focus of the object-glass is too narrow for the observation of the dark lines, it becomes necessary to spread out the image of the star; and to prevent loss of light, it is of importance that this enlargement should be in one direction only; so that the whole of the light received by the object-glass should be concentrated into a fine line of light as narrow as possible, and having a length



not greater than will correspond to the breadth of the spectrum (when viewed in the apparatus), just sufficient to enable the eye to distinguish with ease the dark lines by which it may be crossed. No arrangement tried by us has been found more suitable to effect this enlargement in one direction than a cylindrical lens, which was first employed for this purpose by Fraunhofer. In the apparatus by which the spectra described in our "Note" of February 1863 were observed, the cylindrical lens employed was plano-convex, of 0·5 inch focal length. This was placed within the focus of the object-glass and immediately in front of the slit of the collimator.

The present form of the apparatus is represented in figs. 1 and 2, where the cylindrical lens is marked *a*. This is plano-convex, an inch square, and of about 14 inches focal length. The lens is mounted in an inner tube, *b*, sliding within the tube *c*, by which the apparatus is adapted to the eye end of the telescope. The axial direction of the cylindrical surface is placed at *right angles* to the slit *d*, and the distance of the lens from the slit within the converging pencils from the object-glass is such as to give exactly the necessary breadth to the spectrum.

In consequence of the object-glass being over-corrected, the red and, especially, the violet pencils are less spread out than the pencils of intermediate refrangibility; so that the spectrum, instead of having a uniform breadth, becomes slightly narrower at the red end, and tapers off in a greater degree towards the more refrangible extremity.*

In front of the slit *d*, and over one half of it, is placed a right-angled prism *e*, for the purpose of reflecting the light which it receives from the mirror *f* through the slit. In the brass tube *c* are two holes: by one of these the light is allowed to pass from the mirror to the reflecting-prism *e*; and by means of the other, access to the milled head for regulating the width of the slit is permitted. Behind the slit, and at a distance equal to its focal length, is placed an achromatic collimating lens *g*, made by T. Ross; this has a diameter of 0·6 inch and a focal length of $4\frac{1}{2}$ inches. These proportions are such that the lens receives the whole of the light which diverges from

* The experiment was made of so placing the cylindrical lens that the axial direction of its convex cylindrical surface should be *parallel* with the direction of the slit. The line of light is in this case formed by the lens; and the length of this line, corresponding to the visible breadth of the spectrum, is equal to the diameter of the cone of rays from the object-glass where they fall upon the slit. With this arrangement, the spectrum appears to be spread out, in place of being contracted at the two extremities. Owing to the large amount of dispersion to which the light is subjected, it was judged unadvisable to weaken still further the already feeble illumination of the extremities of the spectrum; and in the examination of the stellar spectra the position of the cylindrical lens with its axis at right angles to the slit, as mentioned in the text, was therefore adopted.

A *plano-concave* cylindrical lens of about 14 inches negative focal length was also tried. The slight advantage which this possesses over the convex form is more than balanced by the inconvenience of the increased length given to the whole apparatus.

the linear image of the star when this is brought exactly within the jaws of the slit.

The dispersing portion of the apparatus consists of two prisms, *h*, each having a refracting angle of about 60° ; they were made by T. Ross, and are of very dense and homogeneous flint glass. The prisms are supported upon a suitable mounting, which permits them to be duly levelled and adjusted. Since the feebleness of the light from the stars limits the observations for the most part to the central and more luminous portions of the spectrum, the prisms have been adjusted to the angle of minimum deviation for the ray D. A cover of brass, *k*, encloses this part of the apparatus; and by this means the prisms are protected from accidental displacement, and from dust.

The spectrum is viewed through a small achromatic telescope *l*, furnished with an object-glass of 0·8 inch diameter and 6·75 inches focal length. This telescope has an adjustment for level at *m*. The axis of the telescope can be lowered and raised, and the tube can be also rotated around the vertical axis of support at *n*. At the focus of the object-glass are fixed two wires, crossing at an angle of 90° . These are viewed, together with the spectrum, by a positive eyepiece *p*, giving a magnifying power of 5·7 diameters. As the eyes of the two observers do not possess the same focal distance, a spectacle-lens, corresponding to the focal difference between the two, was fitted into a brass tube, which slipped easily over the eyepiece of the telescope, and was used or withdrawn as was necessary.

This telescope, when properly adjusted and clamped, is carried by a micrometer-screw *q*, which was constructed and fitted to the instrument by COOKE & SONS. The centre of motion about which it is carried is placed approximately at the point of intersection of the red and the violet pencils from the last prism; consequently it falls within the last face of the prism nearest the small telescope. All the pencils, therefore, which emerge from the prism are, by the motion of the telescope, caused to fall nearly centrically upon its object-glass. The micrometer screw has 50 threads to an inch; and each revolution is read to the hundredth part, by the divisions engraved upon the head. This gives a scale of about 1800 parts to the interval between the lines A and H of the solar spectrum. During the whole of the observations the same part of the screw has been used; and the measures being relative, the inequalities, if any, in the thread of this part of the screw do not affect the accuracy of the results. The eye lens for reading the divisions of the micrometer-screw is shown at *s*.

The mirror *f* receives the light to be compared with that of the star-spectrum, and reflects it upon the prism *e*, in front of the slit *d*. This light was usually obtained from the induction spark taken between electrodes of different metals, fragments or wires of which were held by a pair of small forceps attached

to the insulating ebonite clamp π . Upon a movable stand in the observatory was placed the induction coil, already described by one of us,* in the secondary circuit of which was inserted a Leyden jar, having 140 square inches of tinfoil upon each of its surfaces. The exciting battery, which, for the convenience of being always available, consisted of four cells of Smee's construction, with plates 6 inches by 3, was placed without the observatory. Wires, in connection with this and the coil, were so arranged that the observer could make and break contact at pleasure without removing his eye from the small telescope. This was the more important since, by tilting the mirror f , it is possible, within narrow limits, to alter the position of the spectrum of the metal relatively to that of the star. An arrangement is thus obtained which enables the observer to be assured of the perfect correspondence in relative position in the instrument of the stellar spectrum and the spectrum to be compared with it.

SPECTROGRAPHIC APPARATUS CONSTRUCTED FOR THE PHOTOGRAPHING OF STELLAR SPECTRA

(From *Phil. Trans.*, 1880, Part II., p. 669)

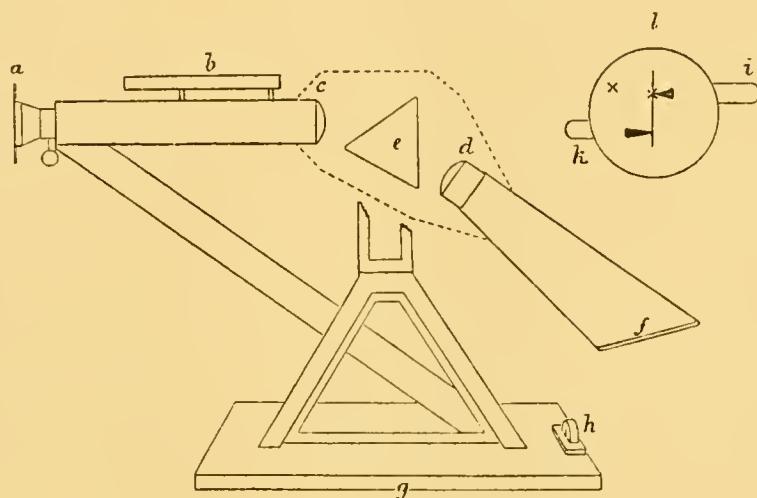
IN consequence of the very limited amount of light received from the stars, it was obviously of the first importance to spread out the spectrum to the smallest amount that would give a sufficiently visible separation of the principal lines to permit of their being easily recognised and measured. Another point in this connection which required consideration was whether a slit should be employed. A slit sufficiently narrow to be of use for the purposes presently to be mentioned would allow a portion only of the light concentrated by the speculum in the star's image to enter the collimator, and would therefore greatly lengthen the exposure required to obtain a photograph. Notwithstanding this serious drawback I determined to use a slit, partly for the sake of a purer spectrum, and partly on account of the facility which a slit would give to obtain a second spectrum for comparison on the same plate with the star's spectrum. The employment of a slit would also make the same apparatus suitable for use upon the moon and planets.

For the material of the prism I selected Iceland spar, as it is very transparent to the ultra-violet rays, and has so much higher a dispersion than quartz that one prism only would be sufficient. The prism has a refracting angle of 60° , and is cut in a plane perpendicular to the axis of the crystal. Such a prism in any one position gives single refraction for light of one refrangibility only, but practically the separation of the two images through

* *Phil. Trans.*, 1864, p. 141.

the range of the spectrum which is photographed is too small sensibly to affect the results.* The prism is fixed in a position of minimum deviation for H. The lenses are of quartz, cut perpendicular to the axis and plano-convex in form. The lens of the collimator is $1\frac{1}{2}$ inch diameter, 10 inches focal length. The lens placed after the prism to form the image on the plate is of the same diameter, $6\frac{1}{2}$ inches focal length.

The form of construction of the spectrum apparatus is shown in the accompanying diagram (fig. 6).



- | | |
|---------------------------|---|
| a. Slit plate. | g. Bevelled edge. |
| b. Tube for collimation. | h. Screw for adjustment in focus of mirror. |
| c, d. Quartz lenses. | i, k. Shutters of slit. |
| e. Prism of Iceland spar. | l. Silver plate with slit. |
| f. Photographic plate. | |

Fig. 6.

The wooden frame which receives the photographic "backs" is made to tilt so as to allow the plate to be brought into a position in which the rays of different refrangibility shall be, as nearly as is possible, in focus together upon the plate. This position was previously found by means of solar light,

* Professor Stokes has permitted me to add the following note, dated January 23, 1875:

"I have worked out the deviations for a prism of 60° of calcareous spar, the axis perpendicular to the bisecting plane of the prism, the line H at minimum deviation and therefore seen single. I have worked out the deviations for B with the results:

Deviation for H ordinary	$34^{\circ} 37' 76$
" " B ordinary	$51'' 32' 49$
" " " extraordinary	$51^{\circ} 32' 36$

"The difference comes smaller than I had expected, only $0' 13$ or $8''$, the spectrum from B to H being over 3° . For a line half way between B and H the difference would be only a quarter of that, or $2''$. The difference comes out practically insensible."

and the frame was then firmly fixed in position before the apparatus was mounted in the telescope.

The photographic plates are $1\frac{1}{2}$ inch long by $\frac{1}{2}$ inch wide, and the length of the photographic spectrum between the lines G and P in the ultra-violet about $\frac{1}{2}$ inch.

The definition is so good that the photographs can be examined with advantage under a low-power microscope, and notwithstanding their small size, about fourteen lines may be counted between the lines H and K.

The apparatus combines very successfully a sufficiently defined separation of the parts of the spectrum with a moderate diminution only of the intensity of the star's light.

The width of the slit which was finally adopted was based on a compromise. The very narrow slit which gave the best photograph of the solar spectrum was found to diminish too seriously the light of the stars, and the slit was then opened until the interval between the edges was about $\frac{1}{350}$ of an inch. When the slit is of this width of opening the solar lines are still well defined, but the number of lines to be counted between H and K is reduced to about seven. I found it was not possible to work with a narrower slit.

The base plate of the apparatus is bevelled at the edges, and slides in the grooves of a second plate, which is firmly screwed to a wooden platform which is attached to the end of the telescope tube (fig. 7). The small convex speculum was removed from the Cassegrain telescope; and the spectrum

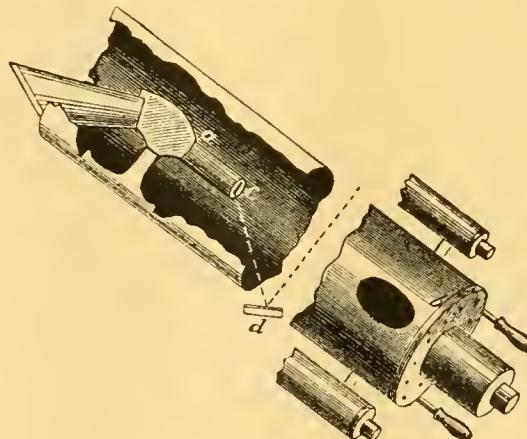


Fig. 7.

apparatus fixed at the end of the tube, as already described, was so adjusted that the slit was brought exactly to the position of the principal focus of the large speculum. The grooves in which the apparatus slides are graduated, so that the apparatus after removal can be replaced exactly in its former position. A final determination of this position was made from the definition of photographs of star spectra.

For the adjustment of the collimator of the spectrum apparatus in the optical axis of the large speculum a tube 6 inches long with cross wires at both ends was fixed on the collimator and parallel to it. Advantage was then taken of the hole in the large speculum. The eye-tube of the Cassegrain was removed, and a small Galilean telescope, magnifying 16 diameters, was fixed in its place. The spectroscope was then so adjusted by suitable screws that the cross wires at the first end of the small tube were made to coincide, when viewed through the Galilean telescope, with those at the farther end of the tube.

Two requirements at once presented themselves, of such primary importance that success was seen to depend upon the perfection of the method adopted to meet them. It was necessary to have a method of bringing the image of the star readily and with exactness upon any desired part of the slit. Further, it was necessary to have a convenient method of continuously watching the star's image when upon the slit during the whole time of the photographic exposure, in order to correct by hand any small inequalities of the motion of the telescope which might throw the star's image off the slit. In a large equatorial there are other sources of small inequalities of motion besides those due to want of uniformity in the clock itself. When it is remembered that the star's image must remain steadily upon a slit $\frac{1}{350}$ th of an inch in width for perhaps an hour, it will be seen how necessary is the power of continuous supervision and of instant control by hand. The following methods were perfectly successful:—

A round thin plate of polished silver (*l*, fig. 6; *c*, fig. 7), $1\frac{1}{2}$ inch in diameter, with a narrow opening in the middle rather longer and wider than the slit itself, was fixed over the slit of the spectroscope. This plate forms a plane mirror, and when the telescope has been brought approximately into position by its finders, the bright image of the star is seen somewhere upon the plate by looking into the small Galilean telescope fixed in the place of the eyepiece of the Cassegrain telescope. Now, if at the same time artificial light is thrown upon the plate, it becomes itself visible, and then the opening in it and the slit within the opening can be distinctly seen at the same time as the image of the star as a bright spot upon it. By the aid of this arrangement there is no difficulty in bringing the star's image by the slow-motion handles of the equatorial readily and with precision upon any part of the slit.

As the position of the star's image even upon the slit itself can be seen, the image being somewhat wider than the slit and therefore not wholly lost within it, it is possible to keep the star in view upon the slit during the whole time the photograph is being taken, and to correct instantly by hand any small departure of the star's image from its proper place upon the slit.

I will now describe how the necessary breadth was given to the spectrum

without the employment of a cylindrical lens. As the star's image is not a point, its linear spectrum has a small breadth, but not more than about half the breadth which is necessary for the lines to be well seen. After the exposure had proceeded sufficiently to produce a linear spectrum, the image of the star was moved upon the slit in the direction of its length, through a space equal to about the apparent diameter of the star's image. The exposure was then continued for a period of about the same length. In this way a photographic spectrum can be obtained of the breadth that is desired by the union of two or more linear spectra. Shortly afterwards the necessary motion of the star in the slit was more conveniently obtained by giving a gaining rate to the driving clock ; then the star travels slowly along the slit, and when it has passed through a distance corresponding to the breadth which is desired for the photographic spectrum, the star is brought back to its first position ; in this way, by a sufficient number of runs of a fixed length, the time required for an exposure can be made up.

The artificial light was thrown upon the silver plate by a small mirror fixed on the side of the telescope tube opposite to the end of the declination axis (*d*, fig. 7). This axis is hollow, and the light passes through it from a lamp suspended at the end. The precaution was taken of making this light pass through a plate of yellow glass.

NEW SPECTROSCOPE ATTACHED TO REFRACTOR

(From *Astr. and Astrophys.*, 1893, p. 117)

THIS instrument was designed primarily for the purpose of mounting upon the 15-inch Refractor belonging to the Royal Society a fine 4-inch Roland grating which was furnished to me by Mr. Brashear.

A condition of fundamental importance in the adaptation of the spectroscope to the telescope is that the instrument shall remain perfectly rigid in all its parts relatively to each other, and also to the optical axis of the telescope, in all positions of the telescope. It appeared to me that this condition would be most certainly secured by making the spectroscope complete and rigid in itself, independently of its attachment to the steel tubes, by which it is supported. The spectroscope if removed from the telescope would remain a complete and rigid instrument.

The firm attachment of this spectroscope to the telescope is carried out by means of three steel tubes of $1\frac{3}{8}$ inch external diameter, which slide in three long brackets strongly bolted to the iron eye end of the steel tube of the telescope. These tubes, as can be seen in the photograph, are further held together and formed into a stiff supporting cage by two iron ring-brackets

through which they pass. The ring-bracket near the ends of the tubes supports the heavy part of the spectroscope, consisting of the grating and prism box; the other ring-bracket supports the collimator near the slit end, and strengthens the tube-cage near the middle of its length.

By means of adjusting screws in these ring-brackets the axis of the collimator can be brought into line with the optical axis of the telescope. The other necessary adjustments are also provided for. By the large milled head on the top of the collimator, the spectroscope, as a whole, can be moved so as to bring the slit to the focal plane of the object-glass for the part of the spectrum under observation; and a fine graduation on the sliding tube enables this adjustment, and also any similar adjustment that may be required for

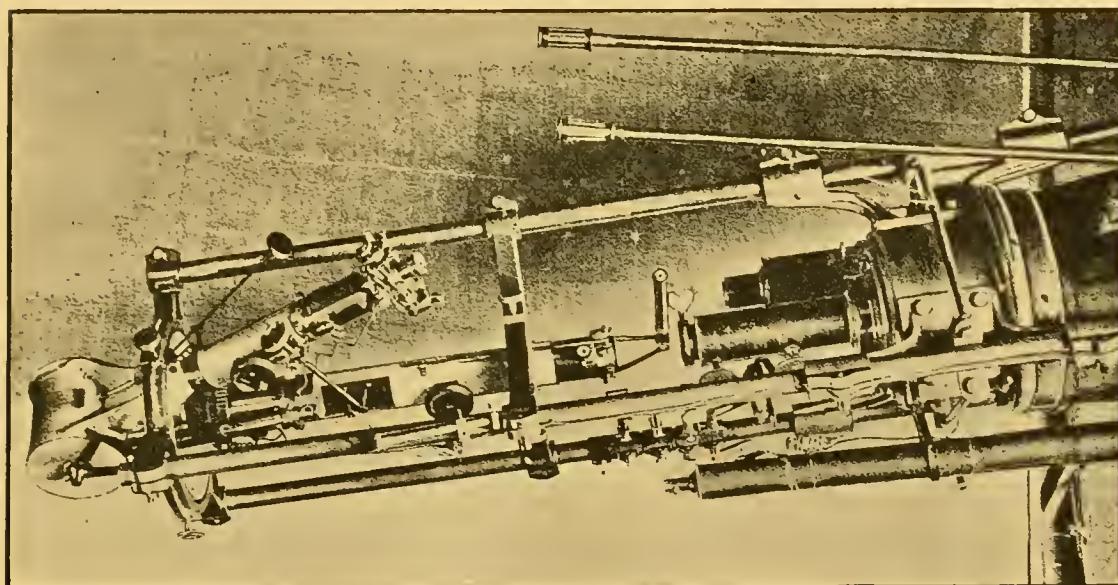


Fig. 8.—THE TULSE HILL SPECTROSCOPE.

changes of temperature, to be found at once after the necessary data have been obtained. The adjustment of the collimator lens can be made by a smaller milled head. By an arrangement, which explains itself in the photograph, the collimator and telescope can be focussed simultaneously.

The collimator, and the telescope, fixed at an angle of 25° , are firmly attached to the grating-box, and are further secured from relative flexure by a gun-metal collar fitting into the iron ring-bracket.

The grating is mounted in an air-tight metal case, provided with shutters to open when it is in use. This case slides into the box against a fixed point so as to secure the grating always taking up the same position. A prism of 37° , silvered on one face, similarly mounted, can take the place of the grating when small dispersion is required.

The grating, or prism, is moveable about the axis of the box, by a rod which is placed conveniently for the hand of the observer. At the top of the box, which is strengthened internally by metal compartments, a sector is fixed on the moveable axis, which is graduated on silver, and is read by a small telescope. The graduated edge of the sector, which can be illuminated by a small incandescent lamp, is divided into spaces of 5', and reads by the aid of the vernier to 10".

The telescope of the spectroscope is provided with a micrometer by Troughton & Simms, the fine webs of which are very successfully illuminated simultaneously from both sides from one small incandescent lamp, on an original plan devised by them. The amount of illumination can be varied by means of a small resistance coil to suit the object under observation. With the feeble illumination which is necessary for most celestial objects, it is not easy to read the number of whole revolutions of the micrometer screw, in the usual way, from the teeth of the comb. A simple form of a revolution-counter is geared into the outer rim of the micrometer head, and turns with it without sensible friction. The micrometer heads and their revolution-counters can be illuminated at pleasure by means of two small moveable incandescent lamps suitably placed above them. The micrometer-screw has 100 threads to the inch ; and when the second order of the grating, ruled to 14.438 to the inch, is in use, about $\frac{23}{100}$ of a revolution are equal to one-tenth metre.

The collimator and telescope have thin cemented lenses of $2\frac{1}{4}$ inches diameter ; that of the collimator is provided with a diaphragm reducing it to 2 inches, which is its effective aperture ; as the collimator has a focal length of 24 inches, and the object-glass of the telescope a ratio of $\frac{f}{15}$. The telescope of the spectroscope has a focal length of 18 inches, and is provided with four eyepieces magnifying respectively 12, 18, 22 and 29 diameters.

For photography the eye-part of the telescope can be replaced by a camera, and the whole instrument rotated through 90° , so as to bring the length of the slit in the direction of the star's motion.

The grating-box can be uncoupled from the collimator and removed from the supporting iron ring, and replaced by a battery of glass prisms, the same telescope and micrometer, or photographic lens and camera, being then attached.

A novelty in this instrument, which will be seen at once to be one of great practical importance, consists of a simple but very effective arrangement by which a star can be brought at once, and kept steadily, within the jaws of the slit. For my primary photographic work on the spectra of the brighter stars, I devised in 1875 a method of bringing and keeping a star within the slit, which is figured and described in my paper "On the Photographic Spectra of the Stars" (*Phil. Trans.*, 1880, p. 673) *:

* See preceding Paper.

"A round thin plate of polished silver, $1\frac{1}{2}$ inch in diameter, with a narrow opening in the middle rather longer and wider than the slit itself, was fixed over the slit of the spectroscope. This forms a plane mirror, and when the telescope has been brought approximately into position by its finders, the bright image of a star is seen somewhere upon the plate by looking into a Galilean telescope fixed in the place of the eyepiece of the Cassegrain telescope. Now if at the same time artificial light is thrown upon the plate, it becomes itself visible and thus the opening in it, and the slit within the opening can be distinctly seen at the same time as the image of the star as a bright point upon it. By the aid of this arrangement there is no difficulty in bringing the star's image by the slow-motion handles of the equatorial readily, and with precision upon any part of the slit. As the position of the star's image even upon the slit itself can be seen, the image being somewhat wider than the slit and therefore not wholly lost within it, it is possible to keep the star in view upon the slit during the whole time the photograph is being taken; and to correct instantly by hand any small departure of the star's image from its proper place upon the slit."

Some improvements and modifications of the original plan have been made to suit the conditions of a spectroscope applied to a refracting telescope. Slit-jaws of speculum metal have been substituted for the silver plate used in 1875. This metal answers the purpose admirably, as it receives and maintains a high polish, and can be fashioned to take very smooth and true edges for the slit.

If the polished surfaces of the jaw-plates were in a plane perpendicular to the optical axis of the telescope, the light after reflection would return upon its path. The plane in which these surfaces lie is, therefore, slightly inclined so as to throw the reflected light sufficiently to one side of its original direction to be caught by a suitably formed reflecting prism placed just outside the converging rays from the object-glass. This prism is provided with a suitable optical arrangement of some magnifying power, and is shown in the photograph in position for use.

At night, when the telescope is directed to the heavens, if the eye is placed at this reflecting eyepiece, a field of stars of about $5'$ in diameter is seen together with the slit crossing it. Very often the faint illumination of the sky is sufficient to enable the slit to be seen, but if necessary a feeble artificial light can be thrown upon the polished surfaces, so as to make the slit visible, but without interfering with the visibility of the images of even faint stars. It is obvious that by means of this arrangement it is quite easy to bring, and also to keep steadily, a star image upon any part of the slit. In the case of suitable double stars wider than about $3''$, the component images are seen well apart, and either of them can with ease be brought and kept within the

slit-jaws. So also in the case of planets and nebulae there is no difficulty in selecting any small part of one of these objects for separate spectroscopic examination.

This reflecting eyepiece is hinged, and when not in use can be turned down out of the way to give room for a large diagonal eyepiece for viewing celestial objects directly, without removing the spectroscope from the steel tubes.

The slit is also provided with the usual reflecting eyepiece, which can be pushed in behind it. I pointed out in my paper of 1879 (*loc. cit.*) that in photographing the spectra of the stars the necessary breadth can be most conveniently obtained by the plan now universally employed, of giving a small motion to the star's image in the direction of the length of the slit. For eye observations it is still necessary to have recourse to cylindrical lenses. For a great number of years I have minimised the inconveniences which such lenses introduce by using the plano-concave instead of the usual plano-convex form.

Perhaps the least objectionable way of using them is to have three, or more, of different cylindrical curvatures fitted into a small brass slide, which goes immediately in front of the eye-lens, and fits equally the different eyepieces. The lens giving the most suitable breadth can be brought into use, and if it be of concave form, without in the least disturbing the focal adjustment of the eyepiece.

If it be preferred to place the cylindrical lens before the slit, the advantage in respect of light will be seen to be in favour of the plano-concave form.

The arrangement for comparison spectra is attached to one of the rods, a reflecting prism of 90° , sending the light upon the small moveable prism immediately in front of the slit. The optical arrangement is such as to completely fill the lens of the collimator with the light which furnishes the spectrum for comparison.

I cannot refrain from expressing my admiration of the great rigidness of every part of the apparatus, as well as of the extremely fine definition both when the prism and the grating are in use; for which the highest credit is due to Messrs. Troughton & Simms; and also to Mr. Brashear for the high qualities of the grating.

I ought to add that a second spectroscope, containing some new points of importance, is now in course of construction for use with the 18-inch Cassegrain telescope, for the photography of the ultra-violet spectra of celestial objects.

THE ULTRA-VIOLET SPECTROSCOPE

(From *Astrophys. Journ.*, vol. i., p. 359, and "Atlas of Representative Stellar Spectra":
Wesley & Son, 1899)

THE spectroscope which I designed and had constructed during the seventies for my original work on photographing the spectra of the stars * was arranged to include the whole of the ultra-violet region of the light from the heavenly bodies which reaches the Earth.

I had at my command a refractor of 15 inches aperture, and a Cassegrain telescope of 18 inches aperture, both belonging to the Royal Society. I chose the latter instrument for my work, notwithstanding the drawback of some want of permanency of the collimation of the mirrors, on account of the freedom of a reflector from the outstanding chromatic aberrations of a refractor, and also because by the employment of Iceland spar for the prism and quartz for the lenses, the whole of the more refrangible part of the spectrum could be photographed, at least as far as the absorption of our atmosphere allows rays of small wave-length to pass.

The Cassegrain telescope, which has mirrors of speculum metal of very fine defining power, was made by Sir H. Grubb. In 1882 it was mounted, by the novel device of a double declination axis, one axis moving within the other, as a twin telescope, together with the 15-inch refractor, upon the same equatorial stand. This instrument has been used chiefly for spectroscopic work, but last year advantage was taken of the fine definition of the specula to make some crucial observations of the character of the image of Nova Aurigæ.†

The early arrangement employed in 1876 to 1879 consisted essentially of a small spectroscope containing a single prism of Iceland spar, and lenses of quartz, the slit of which was placed in the principal focus of the great speculum, eighteen inches in diameter, of the Cassegrain telescope, the small convex speculum having been removed.

In this instrument the plan was adopted for the first time of turning the jaw-plates of the slit into mirrors, in which the objects to which the instrument was directed could be seen by reflection at the same time as the slit itself. In the first instance polished silver was used for the reflecting substance; afterwards very thin plates of quartz, silvered at the back, the edges of which formed the slit; and finally, in the new spectroscope attached to the refractor,‡ speculum metal was found to fulfil very satisfactorily the necessary conditions

* "On the Photographic Spectra of the Stars." *Phil. Trans.*, 1880, Part ii., p. 669.

† In this instrument, which is of course free from chromatic aberration, the images of Nova Aurigæ and of the star near it were indistinguishable in character under a magnifying power of 700 diameters. Both appeared equally stellar. *A. N.* 3211; *A. and A.*, April 1894, p. 314.

‡ See *ante*, p. 19.

of giving a permanently reflecting surface, and furnishing true edges for the slit. In this early instrument the images of celestial objects reflected from the mirror-jaw plates were observed through the hole in the great speculum by means of a small telescope fixed in the place of the eyepiece.

The advantage which this form of spectroscopic arrangement possessed of reducing the loss of light by reflection to that at the surface of one speculum only, was accompanied by some drawbacks. The spectroscope, though made as small as possible, was larger than the four-inch hole in the speculum, and blocked out some light. The adjustments of the spectroscope itself, and also of its relation to the speculum, could only be made with some inconvenience at the top of the tube. For the same reason, unless the telescope was directed to an object very low down, it was necessary, at some loss of time, to unclamp it in declination and bring the spectroscope-end within reach in order to insert or to change the photographic plate.

There was the further disadvantage that in consequence of the large ratio of aperture to focal length of the great speculum, namely, $\frac{f}{7\frac{1}{2}}$, the collimator had to be made very short. Consequently with one prism, to which the spectroscope was necessarily restricted on account of size, either light or the necessary purity of the spectrum had to be sacrificed. If the slit were opened wide enough to just include, or even nearly so, the image of a star, its angular magnitude relatively to the dispersion was too great for the needful resolution of lines, and therefore, as a matter of fact, the slit was always used too narrow to receive more than a part of the light of a star, with the great disadvantage of long exposures.

The new instrument is free from these disadvantages, though in one respect it comes short of the earlier arrangement, since there is additional loss of light from reflection at the second speculum. The Cassegrain telescope is restored to its original form, and the collimator of the new spectroscope passing up through the hole in the large speculum, the slit is placed within the telescope tube at the focal plane after reflection from the small convex speculum.

In fig. 9 the collimator is seen within the telescope tube; in fig. 10 the remaining part of the spectroscope, outside and below the telescope tube, is shown.

Returning to fig. 6, the diagram explains itself. The slit is adjusted by means of a rod, which in fig. 7 is seen to pass below the spectroscope and to terminate in a graduated head.

Behind the slit slides a small shutter which closes the central half of the slit, to protect the part of the plate on which the star's spectrum falls, when, either before or after exposure, narrow comparison spectra are photographed through the outer parts of the slit, above and below the star's spectrum.

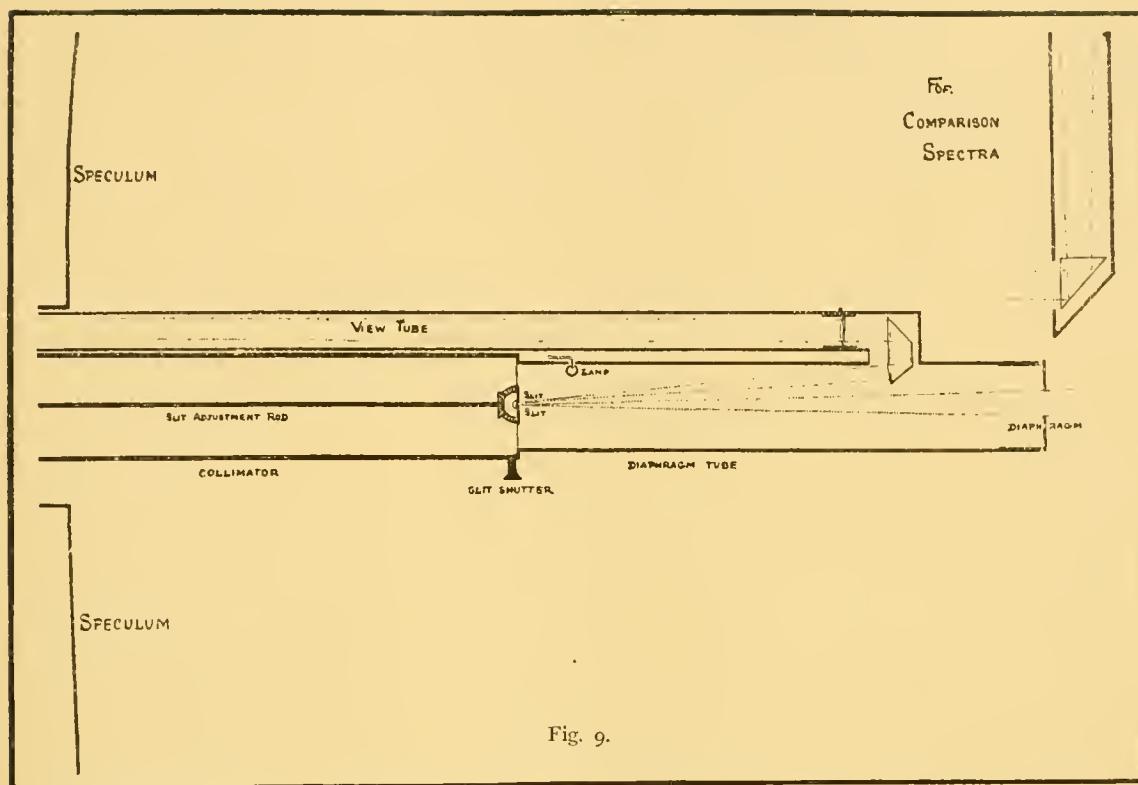


Fig. 9.

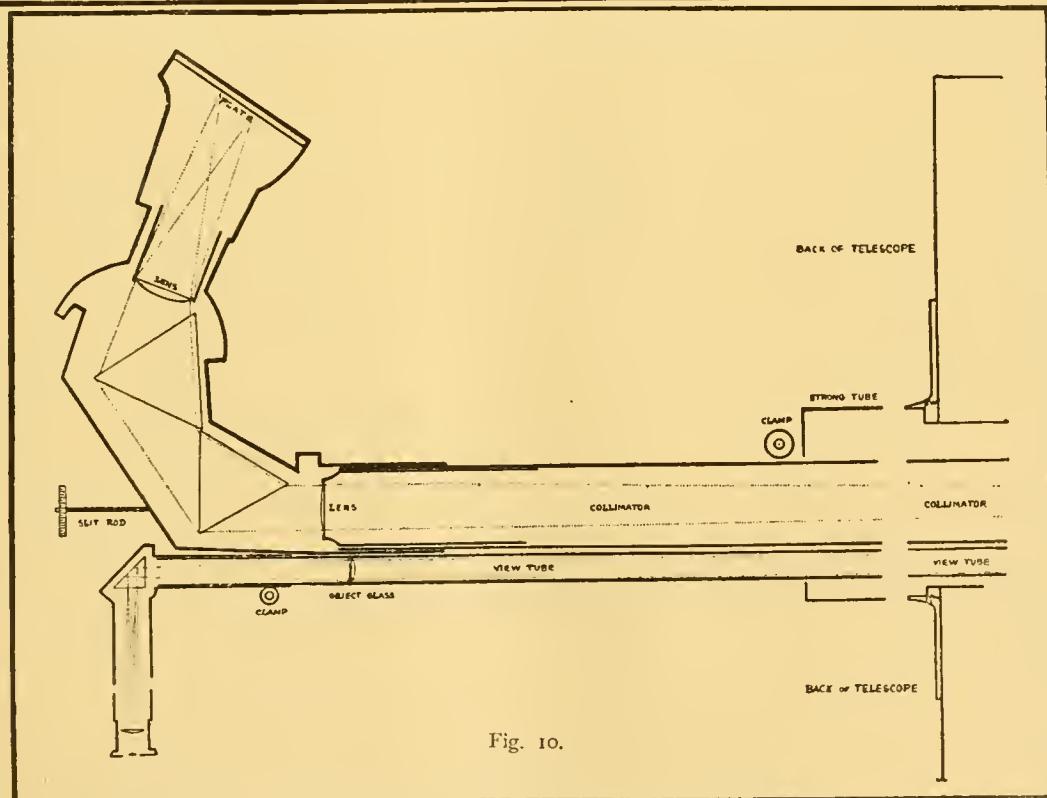


Fig. 10.

THE TULSE HILL ULTRA-VIOLET SPECTROSCOPE.

In front of the slit extends a tube 12 inches long, furnished at the end with a sliding diaphragm having an opening of such a size as to exclude all light except that reflected from the small convex mirror.

A very successful arrangement of the slit-mirror method has been adopted by which the slit, together with a small field of stars, can be conveniently seen by an observer looking into the diagonal eyepiece, shown in fig. 10. This eyepiece, by means of the clamp, can be brought into and then fixed in the position which is most convenient for observation. The polished slit-plates of speculum metal are slightly inclined so that the light which does not pass on through the slit is reflected, as shown in fig. 9, to one side of the diaphragm-tube. There it falls upon the first face of a prism of such a form that after two internal reflections it returns along the small view-tube placed by the side of the collimator. A few inches below the second surface of the prism is placed a small achromatic lens having a focal length equal to its distance from the slit. The rays after passing through it are rendered parallel, and then pass on without loss, until at a little distance from the eyepiece, fig. 7, they encounter a second achromatic lens. This has a focal length of about six inches, and with a suitable eyepiece gives a well-defined and bright view of the small field of stars upon the slit-plates. On a dark night, or when an object of finite magnitude, as a planet or a nebula, is not upon the slit, the opening of the slit becomes lost to view. For the purpose, under these circumstances, of illuminating the slit artificially, a very small incandescent lamp made of ruby glass is inserted through the side of the diaphragm-tube a little way from the slit, fig. 9. It is enclosed so that light passes only upon the slit-jaws. From the position of the lamp it will be seen that its light is not reflected back from the slit in the direction to pass to the observer's eye. The slit-jaws are illuminated by that small part only of the red light of the lamp which is scattered from the mirrors in consequence of imperfect polish. This feeble illumination is found in practice to be just what is needed to show the slit distinctly, without overpowering faint objects. A variable resistance is placed within reach, so as to make it easy to obtain with exactness the precise degree of illumination which is most suitable to each object. From the position of the lamp any light which passes through the slit does not pass on to the collimator-lens, but is absorbed by the blackened inner surface of the tube. The ease with which the slit can, by this arrangement, be placed with precision upon a star, or upon a small part of a planet or of a nebula, is all that can be desired.

In fig. 9 the detached tube terminated by a right-angled reflecting prism forms part of the arrangement for throwing into the slit the light from sparks or flames for comparison. When in use this tube, which slides through an outer tube furnished with the necessary adjusting screws fixed upon the

outside of the telescope-tube, is pushed in until the reflecting prism comes in front of the opening at the end of the diaphragm-tube before the slit. The light from the spark, vacuum tube, or flame outside the great telescope passes through a double quartz-combination fixed in the tube near the outer end, by which it is made to converge to a focus upon the slit, and then to diverge at a little greater angle than is necessary to completely fill the collimator-lens.

When not in use, this tube can be wholly withdrawn outside the telescope-tube, so as not to intercept any light from the great mirror.

Fig. 10 shows the prism-box, which contains two prisms of Iceland spar, each with a refracting angle of 60° . These were made for me by Mr. Hilger, and have been cut very successfully. The smaller prism, which limits the beam that can pass through them, has a length of $2\frac{1}{2}$ inches with a height of $1\frac{1}{2}$ inch.

It was decided to work with the prisms in a fixed position, though this position can be varied from time to time for different parts of the spectrum. The prisms and camera are therefore provided with clamps, by which, when all the necessary adjustments of the prism, of the camera-lens and of the plate-holder have been made, the whole apparatus can be secured rigidly in position. All the different adjustments are provided with divided scales, so that if it were necessary for any reason to dismount any part of it, the instrument could be put back again into its former position with great exactness.

The instrument is provided with two camera-lenses, one of about $5\frac{3}{4}$ inches, which is now in use for nebulae, and a lens of 9 inches for stellar spectra, the larger scale of the spectrum making it more independent of the granulation of the gelatine film. Finally, a camera-lens having a focal length of 15 inches was adopted. The range of spectrum from F to $\lambda 330$ measures about $2\frac{1}{2}$ inches on the photographic plate.

For greater lightness the camera-box is made of aluminium, and as the slit is placed in the direction of the star's motion, this box stands up in a nearly vertical position when the telescope is in the meridian, which is a very favourable one for freedom from flexure.

The spectroscope, as a whole, is secured by means of strong clamps within the large tube which screws on to a plate fixed on the base of the telescope-tube behind the great speculum. It can therefore be attached and removed from the telescope without any derangement of its internal adjustments.

Through the strong supporting tube the spectroscope, as a whole, can slide a few inches for the purpose of a first rough adjustment of the slit to the focal plane; the final adjustment is then made by a fine screw which gives a slow motion to the small convex speculum.

The necessary breadth can be given to the spectra of stars in two ways, either by allowing the star's image to trail in the slit, or by means of a concavo-

cylindrical lens of quartz which is mounted in a short tube, which can take the place of the sliding diaphragm-tube at the end of the tube before the slit.

The long equivalent focal length of the Cassegrain form of telescope is of advantage in many cases of modern astronomical spectroscopy, where it is desirable to have images of considerable dimensions upon the slit-mirrors. It will become, doubtless, of increasing importance to be able to photograph separately the spectra of adjacent parts of the surfaces of nebulae, and of the planets, and to obtain, without enlargement, sufficient breadth of spectrum in the case of very small nebulae. Further, it will be desirable to bring separately upon the slit, and to maintain there, the components of binary and multiple stars, and also the stars involved in nebulae. The Cassegrain form furnishes the means of conveniently obtaining a long equivalent focal length, while the instrument itself, and the building covering it, remain of moderate dimensions.

ON AN AUTOMATIC ARRANGEMENT FOR GIVING BREADTH TO STELLAR SPECTRA ON A PHOTOGRAPHIC PLATE

(From *Astrophys. Journ.*, vol. v., p. 8, 1897)

IN my original paper on the "Photographic Spectra of Stars" (*Phil. Trans.*, 171, Part II., p. 672, 1880) I point out that the necessary breadth may be given to a photographic spectrum, without the use of a cylindrical lens, by simply causing the star's image to travel slowly in the direction of the length of the slit. At present it is usual, the length of the slit being fixed in the direction of the star's motion, by making the rate of the clock slightly fast, to cause the star to travel slowly along the slit, and when it has passed through a distance corresponding to the breadth which is desired for the photographic spectrum, by means of the slow-motion arrangements of the equatorial, to bring the star back to its first position; and in this way, by a sufficient number of runs of a fixed length, to make up the time of exposure which may be required. Without the assistance of an efficient electric control on the speed of the clock, this periodical bringing back of the telescope during a long exposure becomes very irksome, and brings in a serious loss of time. Even if the telescope is provided with a modern electric clock control, the method of successive runs by hand is troublesome and fatiguing, with the very long exposure so often necessary.

A few years ago an automatic arrangement suggested itself to me by which any desired amount of breadth could be given to photographic spectra with great precision and without interference by hand, except so far as may be required by change of refraction or from error of the clock-rate. In this plan of working the clock must not be fast, but accurately adjusted to the

motion of the stars, so that the star's image would remain fixed at any point of the slit at which it was put. Then, by means of an adjustable eccentric cam, introduced between the clock and the driving-screw, the stellar image is made to oscillate backwards and forwards about its mean position to any extent that may be desired. It is necessary to have the means of adjusting the amount of eccentricity to the breadth of spectrum desirable with the spectroscope which is in use; and also the means of removing, at pleasure, the eccentric motion when it is not required.

I took some spectra by this method some years ago, but the wheel which I then employed could not be made sufficiently eccentric. Recently I have had constructed a very simple eccentric arrangement which fulfils these conditions.

The clock-motion on its way to the driving-screw passes through two wheels gearing into each other, of the same diameter and of the same number of teeth. One of the wheels is provided with a cam by which the axis can be moved outside the centre of figure of the wheel. This is effected by moving a small lever on the front of the wheel, which can then be fixed by a clamp in a position corresponding to any desired amount of eccentricity, or breadth of spectrum, within the range furnished by the cam. It is only necessary to bring back the lever to its first position, and to screw up the clamp, to make the wheel concentric, when the clock-motion will be transmitted to the driving-screw without alteration of rate.

It is obvious that when the wheel is made eccentric, the star will slowly travel to and fro about its mean position. The time required to make a complete revolution in my instrument is about two minutes.

It should be pointed out that, as the teeth of the eccentric wheel alternately approach and recede from the other wheel during each revolution, the teeth of both wheels should be long and suitably shaped, so as to allow of considerable interpenetration when the centre of figure of the eccentric wheel is on the side of the axis which is nearer to the other wheel.

When such an eccentric wheel is employed the exposure increases towards the ends of the runs, that is, towards the two edges of the spectrum. If the unequal photographic action be considered an objection, some other mechanical arrangement may be substituted for the eccentric wheel. For instance, a suitable automatic action upon the electric control of the clock, or upon a "mouse wheel." A simpler plan is to have both wheels of the pair concentric, but one of them furnished on one half of its circumference with one tooth, or at most two teeth more, and on the other half with the same number of teeth fewer than the number required to transmit the clock-motion without alteration. The difference in the number of teeth would be too small to prevent good gearing of the wheels; and in this case the exposure would be uniform throughout the runs, and the photographs uniform throughout the breadth of the spectrum.

This plan was finally adopted. In my instrument the number of teeth on the first wheel of the pair is 50, so that one half of the second wheel has 24 teeth, and the other half 26; this difference in the number of the teeth is too small to interfere with the good gearing of the two wheels. It is obvious that after one whole revolution of the wheels, provided the clock-rate has been accurately adjusted, the star's image on the slit will be again precisely at the place where it was at the commencement of the run, notwithstanding that, during the first half of the revolution, the star moved uniformly from this normal position, and during the second half moved back, through the same space, to its original place. In this way we have an automatic ceaseless to-and-fro motion of the star in the slit, quite uniform in both directions, and therefore giving an uniform exposure to the photograph throughout the breadth of the spectrum.

Of course, it is a matter for calculation in the case of each telespectroscope as to the most suitable ratio between the number of teeth on the two halves of the wheel.

With such a wheel the breadth of the spectrum will, indeed, vary with the star's declination; but by making this breadth a little greater than is absolutely necessary for stars of no declination, the breadth remains sufficient for a large range of declination. Any difficulty from this cause might easily be met by having two or three transferable wheels with different teeth-ratios.

By the use of an automatic mechanical arrangement not only will the personal fatigue of the observer be greatly lessened, but, what is of no little importance in a variable climate, the necessary time of exposure will be reduced, for every moment of the exposure will tell upon the plate, since there will come in no interruptions of photographic action, through any want of immediate and accurate bringing back of the star at the end of each run, as can scarcely fail to be the case when it has to be done by hand.

HAND SPECTRUM-TELESCOPE

(From *Proc. Roy. Soc.*, vol. xvi., p. 241, 1868)

THE instrument described in this paper was contrived in the summer of 1866, for the purpose of observing the spectra of meteors and their trains. The special suitability of this apparatus, as a *hand-spectroscope*, for the examination of the spectra of the lights which may be seen about the sun during the total solar eclipse of next year, induces me to offer a description of it to the Royal Society.

The apparatus consists essentially of a direct-vision prism placed in front of a small achromatic telescope.

The achromatic object-glass marked α is 1·2 inch in diameter, and has a focal length of about 10 inches. The eyepiece (β) consists of two plano-convex lenses. As a large field of view is of great importance, especially for its use as a meteor-spectroscope, the field-lens is made of nearly the same diameter as the object-glass. The imperfect definition at the margin of the field is not of much practical importance, as the spectra can be brought for examination into the centre of the field. The field-lens is fixed in a sliding

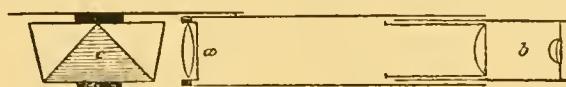


Fig. 11.

tube, which permits the distance between the two lenses of the eyepiece to be altered; in this way the magnifying power of the instrument may be varied within certain limits at pleasure. Before the object-glass is fixed a direct-vision prism (c), consisting of one prism of dense flint glass and two prisms of crown glass.

The field of view of my apparatus embraces an area of sky of about 7° in diameter. The spectrum of a bright star has an apparent length of nearly 3° . The spectrum of the Great Nebula in Orion appears as two bright lines, one of them broad, crossed by a faint continuous spectrum. The magnifying power of the telescope is insufficient to show the three distinct lines of which the spectrum of the nebula consists. The continuous spectrum is due to the stars of the trapezium, and the other fainter stars scattered over the nebula.

For the purpose of testing the efficiency of this instrument as a meteor-spectroscopic, I observed the spectra of fireworks seen from a distance of about three miles. The bright lines of the metals contained in the fireworks were seen with great distinctness. I was able to recognize sodium, magnesium, strontium, copper, and some other metals.

Unfortunately I was prevented from making the use of the instrument which I had intended at the display of meteors in November 1866. I have, however, great confidence in the suitability of the apparatus for the prismatic observation of meteors and their trains.

As the instrument is not provided with a slit, it is applicable only to bright objects of small size, or to objects so distant as to subtend but a very small angle. It is obvious that if the object has a diameter smaller in one direction than in any other, as would usually be the case with the trains of meteors, the instrument should be rotated to take advantage of the form of the object. The most favourable position will be when the smallest diameter of the object is perpendicular to the height of the prisms. In this way I have seen the lines of Fraunhofer in the spectrum of the moon when a very narrow crescent.

In the case of objects which appear as points, a small breadth may be given to the spectrum by a cylindrical lens fitted in a little cap which slips over the eye-lens, and is placed next to the eye.

As some of the advantages which this instrument possesses over an ordinary spectroscope, or over a prism held before the eye, may be stated the comparatively large amount of light which the object-glass collects, the great facility for instantly pointing the instrument to the object desired, which the large field of view affords, and in some cases the magnifying power of the instrument.

It may perhaps be mentioned that secret signals might be conveyed at night by means of the temporary introduction of certain suitable substances, as preparations of lithium, copper, strontium, etc., into the flame of a lamp giving a continuous spectrum : the presence of the bright lines due to these substances would not be perceived except by an observer provided with a spectrum-telescope, to whom they might convey information in accordance with a previous arrangement.

This little instrument, held in the hand and directed to the place of the sun during its eclipse in 1868, might enable an observer, who was not provided with larger apparatus, to give an answer to the important question whether the bright prominences are self-luminous or reflect solar light. At least it would be possible for him to determine the general character of the spectrum of a bright prominence so far as to learn whether it is continuous or consists of bright lines. On account of the low magnifying power of the instrument, the red prominence would appear sufficiently small to permit of bright lines being distinguished on its spectrum, if such should exist.

The instrument should be previously focussed by the observer on the moon, or some distant object.

Should a portion of the sun's limb be visible, the instrument must be rotated until the spectrum of the little projecting prominence appears in a direction parallel to that of the spectrum of the sun's limb, and is not overlapped by it. Perhaps a diaphragm across the field of view and cutting off about one-third of it would be an advantage, as the spectrum of the sun's limb might be concealed behind it. The eye, relieved in this way from the bright solar spectrum, would be in a more favourable state to examine the fainter spectrum of the red prominence.

Four of these instruments, made by Mr. Browning, have been sent out by the Royal Society to India, to be placed in the hands of observers stationed at different places along the central line of the eclipse. This instrument would be specially suitable for use at sea.

Postscript.—Mr. Browning has recently suggested a method of diminishing the apparent velocity of meteors by the use of a concave cylindrical lens placed with its axis perpendicular to the direction of their motion. This mode of

observing may be applied to the spectrum-telescope by substituting, when required, a plano-convex cylindrical lens for the eye-lens of the eyepiece. If this lens be placed with its axis parallel to the height of the compound prism before the object-glass, and if the telescope be held in a position such that the direction in which the light of the meteor is dispersed is perpendicular to that of its motion, the spectrum of the meteor will be magnified, as when the ordinary eye-lens is employed, but the apparent velocity of the meteor will be less by an amount equal to the magnifying power of the eye-lens.

ON A REGISTERING SPECTROSCOPE

(From *Proc. Roy. Soc.*, vol. xix., p. 317, 1871)

THE short duration of the totality of the solar eclipse of December last led me to seek some method by which the positions of lines observed in the spectrum of the corona might be instantly registered without removing the eye from the instrument, so as to avoid the loss of time and fatigue to the eye of reading a micrometer-head, or the distraction of the attention and other inconveniences of an illuminated scale.

After consultation with the optician Mr. Grubb, it seemed that this object could be satisfactorily accomplished by fixing in the eyepiece of the spectroscope a pointer which could be moved along the spectrum by a quick-motion screw, together with some arrangement by which the position of this pointer, when brought into coincidence with a line, could be instantly registered.

I was furnished by Mr. Grubb with an instrument fulfilling these conditions, and also with a similar instrument with some modifications by Mr. Ladd, in time for the observation of the eclipse.

Unfortunately, at my station at Oran, heavy clouds at the time of totality prevented their use on the corona; but they were found so convenient for the rapid registration of spectra that it appears probable that similar instruments may be of service for other spectrum observations.

In these instruments the small telescope of the spectroscope is fixed, and at its focus is a pointer which can be brought rapidly upon any part of the spectrum by a screw-head outside the telescope. The spectrum and pointer are viewed by a positive eyepiece which slides in front of the telescope, so that the part of the spectrum under observation can always be brought to the middle of the field of view. The arm carrying the pointer is connected by a lever with a second arm, to the end of which are attached two needles, so that these move over about two inches when the pointer is made to traverse the spectrum from the red to the violet. Under the extremity of the arm fitted with the needles is a frame containing a card, firmly held in it by two

pins which pierce the card. This frame containing the card can be moved forward so as to bring in succession five different portions of the card under the points of the needles ; on each of these portions of the card a spectrum can be registered.

The mode of using the instrument is obvious. By means of the screw-head at the side of the telescope, the pointer can be brought into coincidence with a line ; a finger of the other hand is then pressed upon one of the needles at the end of the arm which traverses the card, and the position of the line is instantly recorded by a minute prick on the card. A bright line is distinguished from a dark line by pressing the finger on both needles, by which a second prick is made, immediately below the other. In all cases the position of the line is registered by the same needle, the second needle being used to denote that the line recorded is a bright one.

It was found that from ten to twelve Fraunhofer lines could be registered in about fifteen seconds, and that, when the same lines were recorded five times in succession on the same card, no sensible difference of position could be detected between the pricks registering the same line in the several spectra.

It is obvious that, by registering the spectra of different substances on the card, a ready method is obtained of comparing the relative positions of the lines of their spectra.

Each spectroscope was furnished with a compound prism, which was made by Mr. Grubb, and gave a dispersion equal to about two prisms of dense glass with a refracting angle of 60° .

Postscript.—I have just learned that in a spectroscope contrived by Professor Winlock for observing the eclipse of December 22, 1870, the positions of the observing-telescope are registered by marks made upon a plate of silvered copper.—February 3, 1871.

Section II
SPECTRA OF THE FIXED STARS

LIST OF PAPERS

- “On the Lines of the Spectra of some of the Fixed Stars.” (And Dr. Miller.)
Proc. Roy. Soc., vol. xii., p. 444, 1863. P. 42.
- “On the Spectra of some of the Fixed Stars.” (And Dr. Miller.)
Phil. Trans., vol. cliv., pp. 413–435, 1864. P. 44.
- “Physical and Chemical Constitution of the Fixed Stars and Nebulæ.”
(Lecture.)
Roy. Inst. Proc., 1866, vol. iv., p. 441.
- “On the Photographic Spectra of Stars.”
Proc. Roy. Soc., vol. xxv., p. 445, 1876. P. 62.
- “On the Photographic Spectra of the Stars.” (With maps.)
Phil. Trans., 1880, Part II., p. 669. P. 63.
- “On the Limit of Solar and Stellar Light in the Ultra-Violet Part of the Spectrum.”
Proc. Roy. Soc., vol. xlvi., p. 134, 1889. P. 80.
- “On a New Group of Lines in the Photographic Spectrum of Sirius.”
(And Mrs. Huggins.)
Proc. Roy. Soc., vol. xlvi., p. 216, 1890. P. 82.
- “On the Spectrum of Wolf and Rayet’s Bright-line Stars in Cygnus.”
(And Mrs. Huggins.)
Proc. Roy. Soc., vol. xlix., p. 33, 1890. P. 83.
- “Spectres des Étoiles doubles colorées.”
Compt. rend., Oct. 11, 1897.

"Note on Oxygen in Helium Stars."

Ast. Nach., Bd. 149, S. 231, 1899. P. 96.

"Nitrogen in some Helium Stars."

Ast. Nach., Bd. 150, S. 109, 1899. P. 97.

"Results of Spectrum Analysis applied to the Heavenly Bodies."
(Lecture.)

Brit. Ass. Adv. Sci. Report, 1866, p. 140. P. 485.

"Recent Spectroscopic Observations."

Quart. Journ. Sci., vol. vi., p. 209. (Article.)

"Further Results of Spectrum Analysis applied to the Heavenly Bodies."
(Lecture.)

Proc. Roy. Inst., vol. v., p. 475.

"Spectroscopic Observations of Stars and Nebulæ." (Review.)

Month. Not., vol. xxxii., p. 359.

"Presidential Address, British Association for the Advancement of Science."

Report, Brit. Ass. Adv. Sci., 1891, p. 1. P. 504.

"Spectroscopic Notes."

Astrophys. Journ., vol. vi., p. 322.

"Later Work on the Spectra of the Stars."

Note, p. 97.

HISTORICAL STATEMENT

(From the *Nineteenth Century Review*, June 1897)

IT is not easy for men of the present generation, familiar with the knowledge which the new methods of research of which I am about to speak have revealed to us, to put themselves back a generation, into the position of the scientific thought which existed on these subjects in the early years of the Queen's reign. At that time any knowledge of the chemical nature and of the physics of the heavenly bodies was regarded as not only impossible of attainment by any methods of direct observation, but as, indeed, lying altogether outside the limitations imposed upon man by his senses, and by the fixity of his position upon the earth.

It could never be, it was confidently thought, more than a matter of presumption, whether even the matter of the sun, and much less that of the stars, were of the same nature as that of the earth, and the unceasing energy radiated from it due to such matter at a high temperature. The nebular hypothesis of Laplace at the end of the last century required, indeed, that matter similar to that of the earth should exist throughout the solar system ; but then this hypothesis itself needed for its full confirmation the independent and direct observation that the solar matter was terrestrial in its nature. This theoretical probability in the case of the sun vanished almost into thin air when the attempt was made to extend it to the stellar hosts ; for it might well be urged that in those immensely distant regions an original difference of the primordial stuff as well as other conditions of condensation were present, giving rise to groups of substances which have but little analogy with those of our earthly chemistry.

About the time of the Queen's accession to the throne the French philosopher Comte put very clearly in his "Cours de Philosophie positive" the views then held, of the impossibility of direct observations of the chemical nature of the heavenly bodies. He says :

On conçoit, en effet, que nous puissions conjecturer, avec quelque espoir de succès, sur la formation du système solaire dont nous faisons partie, car il nous présente de nombreux phénomènes

parfaitement connus, susceptibles peut-être de porter un témoignage décisif de sa véritable origine immédiate. Mais quelle pourrait être, au contraire, la base rationnelle de nos conjectures sur la formation des soleils eux-mêmes? Comment confirmer ou infirmer à ce sujet, d'après les phénomènes, aucune hypothèse cosmogonique, lorsqu'il n'existe vraiment en ce genre aucun phénomène exploré, ni même, sans doute, EXPLORABLE? [The capitals are mine.]

We could never know for certain, it seemed, whether the matter and the forces with which we are familiar are peculiar to the earth, or are common with it to the midnight sky,

All sow'd with glistening stars more thicke than grasse,
Whereof each other doth in brightnesse passe;

for how could we extend the methods of the laboratory to bodies at distances so great that even the imagination fails to realise them?

The only known communication from them which reaches us across the gulf of space is the light which tells us of their existence. Fortunately this light is not so simple in its nature as it seems to be to the unaided eye. In reality it is very complex; like a cable of many strands, it is made up of light rays of many kinds. Let this light-cable pass from air obliquely through a piece of glass, and its separate strand-rays all divide, each turning its own way, and then go on apart. Make the glass into the shape of a wedge or prism, and the rays are twice widely scattered.

First the flaming red
Sprang vivid forth: the tawny orange next;
And next delicious yellow; by whose side
Fell the kind beams of all-refreshing green.
Then the pure blue, that swells autumnal skies,
Ethereal played; and then, of sadder hue,
Emerged the deepened indigo, as when
The heavy-skirted evening droops with frost;
While the last gleamings of refracted light
Died in the fainting violet away.

Within this unravelled starlight exists a strange cyptography. Some of the rays may be blotted out, others may be enhanced in brilliancy. These differences, countless in variety, form a code of signals, in which is conveyed to us, when once we have made out the cipher in which it is written, information of the chemical nature of the celestial gases by which the different light rays have been blotted out, or by which they have been enhanced. In the hands of the astronomer a prism has now become more potent in revealing the unknown than even was said to be "Agrippa's magic glass."

It was the discovery of this code of signals, and of its interpretation, which made possible the rise of the new astronomy. We must glance, but very briefly, at some of the chief steps in the progress of events which slowly led up to this discovery.

Newton, in his classical work upon the solar spectrum, failed, through some strange fatality, to discover the narrow gaps wanting in light, which, as dark lines, cross the colours of the spectrum and constitute the code of symbols. His failure is often put down to his using a round hole in place of a narrow slit, through the overlapping of the images of which the dark lines failed to show themselves. Though Newton did use a round hole, he states distinctly in his "Optics" that later he adopted a narrow opening in the form of a long parallelogram—that is, a true slit—at first one-tenth of an inch in width, then only one-twentieth of an inch, and at last still narrower. These conditions under which Newton worked were such as should have shown him the dark lines upon his screen. Professor Johnson has recently repeated Newton's experiments under strictly similar conditions, with the result that the chief dark lines were well seen. For some reason Newton failed to discover them. A possible cause may have been the bad annealing of his prism, though he says that it was made of good glass and free from bubbles.

The dark lines were described first by Wollaston in 1792, who strangely associated them with the boundaries of the spectral colours, and so turned contemporary thought away from the direction in which lay their true significance. It was left to Fraunhofer in 1815, by whose name the dark lines are still known, not only to map some 600 of them, but also to discover similar lines, but differently arranged, in several stars. Further, he found that a pair of dark lines in the solar spectrum appeared to correspond in their position in the spectrum, and in their distance from each other, to a pair of bright lines which were nearly always present in terrestrial flames. This last observation contained the key to the interpretation of the dark lines as a code of symbols but Fraunhofer failed to use it; and the birth of astrophysics was delayed. An observation by Forbes at the eclipse of 1836 led thought away from the suggestive experiments of Fraunhofer; so that in the very year of the Queen's accession the knowledge of the time had to be summed up by Mrs. Somerville in the negation: "We are still ignorant of the cause of these rayless bands."

Later on, the revelation came more or less fully to many minds. Foucault, Balfour Stewart, Ångström prepared the way. Prophetic guesses were made by Stokes and by Lord Kelvin. But it was Kirchhoff who, in 1859, first fully developed the true significance of the dark lines; and by his joint work with Bunsen on the solar spectrum proved beyond all question that the dark lines in the spectrum of the sun are produced by the absorption of the vapours of the same substances, which when suitably heated give out corresponding bright lines; and, further, that many of the solar absorbing vapours are those of substances found upon the earth. The new astronomy was born.*

Soon after the close of 1862, in collaboration with Dr. W. A. Miller,

* See Introduction to Part I., "Observatory and Instruments."

I sent a preliminary note to the Royal Society, "On the Lines of some of the Fixed Stars," in which we gave diagrams of the spectra of Sirius, Betelgeux, and Aldebaran, with the statement that we had observed the spectra of some forty stars, and also the spectra of the planets Jupiter and Mars. It was a little remarkable that on the same day on which our paper was to be read, but some little time after it had been sent in, news arrived there from America that similar observations on some of the stars had been made by Mr. Rutherford. A very little later similar work on the spectra of the stars was undertaken in Rome by Secchi, and in Germany by Vogel.

In February 1863 the strictly astronomical character of the observatory was further encroached upon by the erection, in one corner, of a small photographic tent furnished with baths and other appliances for the wet collodion process. We obtained photographs, indeed, of the spectra of Sirius and Capella; but from want of steadiness and more perfect adjustment of the instruments, the spectra, though defined at the edges, did not show the dark lines as we expected. The dry collodion plates then available were not rapid enough; and the wet process was so inconvenient for long exposures, from irregular drying, and draining back from the positions in which the plates had often to be put, that we did not persevere in our attempts to photograph the stellar spectra. I resumed them with success in 1875, as we shall see further on.

Whenever the nights were fine, our work on the spectra of the stars went on, and the results were communicated to the Royal Society in April 1864; after which Dr. Miller had not sufficient leisure to continue working with me. The general accuracy of our work, so far as it was possible with the instruments at our disposal, is shown by the good agreement of the spectra of Aldebaran and Betelgeux with the observations of the same stars made later in Germany by Vogel.

It is obviously unsafe to claim for spectrum comparisons a greater degree of accuracy than is justified by the resolving power employed. When the apparent coincidences of the lines of the same substance are numerous, as in the case of iron; or the lines are characteristically grouped, as are those of hydrogen, of sodium, and of magnesium, there is no room for doubt that the same substances are really in the stars. Coincidence with a single line may be little better than trusting to a bruised reed; for the stellar line may, under greater resolving power, break up into two or more lines, and then the coincidence may disappear. As we shall see presently, the apparent position of the star-line may not be its true one, in consequence of the earth's or the star's motion in the line of sight. Our work, however, was amply sufficient to give a certain reply to the wonder that had so long asked in vain of what the stars were made. The chemistry of the solar system was shown to prevail, essentially at least, wherever a star twinkles. The stars were undoubtedly suns after the

order of our sun, though not all at the same evolutional stage, older or younger it may be, in the life-history of bodies of which the vitality is heat. Further, elements which play a chief *rôle* in terrestrial physics, as iron, hydrogen, sodium, magnesium, calcium, were found to be the first and the most easily recognised of the earthly substances in the stars.

I pass on at once, therefore, to the year 1876, in which by the aid of the new dry plates, with gelatine films, introduced by Mr. Kennett, I was able to take up again, and this time with success, the photography of the spectra of the stars, of my early attempts at which I have already spoken.

By this time I had the great happiness of having secured an able and enthusiastic assistant, by my marriage in 1875.

The great and notable advances in astronomical methods and discoveries by means of photography, since 1875, are due almost entirely to the great advantages which the gelatine dry plate possesses for use in the observatory, over the process of Daguerre, and even over that of wet collodion. The silver-bromide gelatine plate, which I was the first, I believe, to use for photographing the spectra of stars, except for its grained texture, meets the need of the astronomer at all points. This plate possesses extreme sensitiveness ; it is always ready for use ; it can be placed in any position ; it can be exposed for hours ; lastly, immediate development is not necessary, and for this reason, as I soon found to be necessary in this climate, it can be exposed again to the same object on succeeding nights ; and so make up by successive instalments, as the weather may permit, the total long exposure which may be needful.

The power of the eye falls off as the spectrum extends beyond the blue, and soon fails altogether. There is therefore no drawback to the use of glass for the prisms and lenses of a visual spectroscope. But while the sensitiveness of a photographic plate is not similarly limited, glass, like the eye, is imperfectly transparent, and soon becomes opaque, to the parts of the spectrum at a short distance beyond the limit of the visible spectrum. To obtain, therefore, upon the plate a spectrum complete at the blue end of stellar light, it was necessary to avoid glass, and to employ instead Iceland spar and rock crystal, which are transparent up to the limit of the ultra-violet light which can reach us through our atmosphere. Such a spectroscope was constructed and fixed with its slit at the focus of the great speculum of the Cassegrain telescope.

How was the image of a star to be easily brought, and then kept, for an hour, or even for many hours, precisely at one place on a slit so narrow as about the one two-hundredth of an inch ? For this purpose the very convenient device was adopted of making the slit-plates of highly polished metal, so as to form a divided mirror, in which the reflected image of a star could be observed from the eye end of the telescope by means of a small telescope fixed within

the central hole of the great mirror. A photograph of the spectrum of α Lyrae, taken with this instrument, was shown at the Royal Society in 1876.

In the spectra of such stars as Sirius and Vega, there came out in the ultra-violet region, which up to that time had remained unexplored, the completion of a grand rhythmical group of strong dark lines, of which the well-known hydrogen lines in the visible region form the lower members. Terrestrial chemistry became enriched with a more complete knowledge of the spectrum of hydrogen from the stars. Shortly afterwards, Cornu succeeded in photographing a similar spectrum in his laboratory from earthly hydrogen.

I presented in 1879 a paper, with maps, to the Royal Society, on the photographic spectra of the stars, which was printed in their *Transactions* for 1880. In this paper, besides descriptions of the photographs, and tables of the measures of the positions of the lines, I made a first attempt to arrange the stars in a possible evolutional series from the relative behaviour of the hydrogen and the metallic lines.

In this series, Sirius and Vega are placed at the hotter and earlier end; Capella and the sun, at about the same evolutional stage, somewhere in the middle of the series; while at the most advanced and oldest stage of the stars which I had then photographed, came Betelgeux, in the spectrum of which the ultra-violet region, though not wanting, is very greatly enfeebled.

Shortly afterwards, I directed the photographic arrangement of combined spectroscope and telescope to the nebula in Orion, and obtained for the first time information of the nature of its spectrum beyond the visible region. One line a little distance on in the ultra-violet region came out very strongly on the plate. If this kind of light came within the range of our vision, it would no doubt give the dominant colour to the nebula, in place of its present blue-greenish hue. Other lines of the hydrogen series, as might be expected, were seen in the photograph, together with a number of other bright lines.

NOTE ON THE LINES IN THE SPECTRA OF SOME OF THE FIXED STARS

(From *Proc. Roy. Soc.*, vol. xii., p. 444, 1863)

THE recent detailed examination of the solar spectrum, and the remarkable observations of Kirchhoff upon the connection of the dark lines of Fraunhofer with the bright lines of artificial flames, having imparted new interest to the investigation of spectra, it has appeared to the authors of the present note that the Royal Society may not consider a brief account of their recent inquiry upon the spectra of some of the self-luminous bodies of the heavens unworthy of attention, although the investigation is as yet far from complete.

After devoting considerable time to the construction of apparatus suitable to this delicate branch of inquiry, they have at length succeeded in contriving an arrangement which has enabled them to view the lines in the stellar spectra in much greater detail than has been figured or described by any previous observer. The apparatus also permits of the immediate comparison of the stellar spectra with those of terrestrial flames. The accompanying drawing shows with considerable accuracy the principal lines which the authors have seen in Sirius, Betelgeux, and Aldebaran, and their position relatively to the chief solar lines.

Without at present describing in detail, as they propose to do when the experiments are completed, the arrangements of the special apparatus employed,

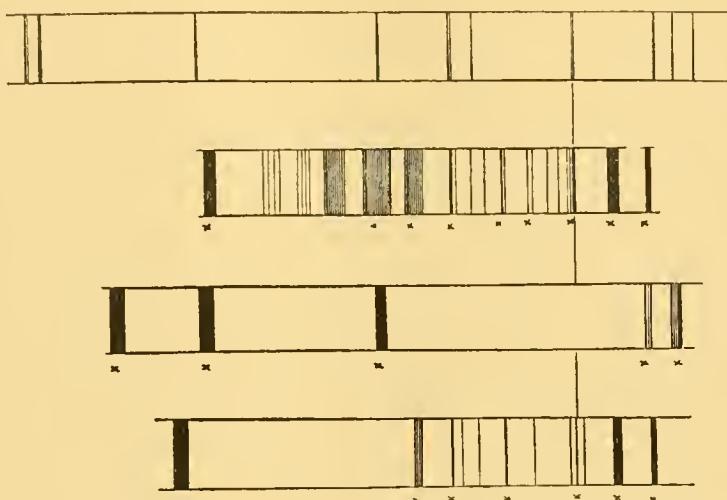


Fig. 12.

it may be sufficient to state that it is attached to an achromatic telescope of 10 feet focal length, mounted in the observatory of Mr. Huggins at Upper Tulse Hill. The object-glass, which has an aperture of 8 inches, is a very fine one by Alvan Clark of Cambridge, U.S.; the equatorial mounting is by Cooke of York, and the telescope is carried very smoothly by a clock motion.

It may further be stated that the position in the stellar spectra corresponding to that of Fraunhofer's line D, from which the others are measured, has been obtained by coincidence with a sodium line, the position of which in the apparatus was compared directly with the line D in the solar spectrum.

The lines in the drawings against which a mark is placed have been measured.

Addendum.—Since the foregoing Note was presented to the Royal Society, the authors have learned that a paper on the same subject, accompanied by

diagrams of the spectra of the Moon, Jupiter, Mars, and several of the fixed stars, by Mr. L. M. Rutherford, has appeared in the January Number of the *American Journal of Science* for the current year. The method of observing finally employed by Mr. Rutherford much resembles that adopted by the authors of this Note.

They therefore desire to add that, during the past twelvemonth, they have examined the spectra of the Moon, Jupiter, and Mars, as well as of between thirty and forty stars, including those of Arcturus, Castor, α Lyrae, Capella, and Procyon, some of the principal lines of which they have measured approximatively. They have also observed β and γ Andromedae, α , β , ϵ and η Pegasi, Rigel, η Orionis, β Aurigae, Pollux, γ Geminorum, α , γ and ϵ Cygni, α Trianguli, ϵ , ζ , and η Ursae Majoris, α , β , γ , ϵ and η Cassiopeiae, and some others.—[Feb. 21, 1863.]

ON THE SPECTRA OF SOME OF THE FIXED STARS

(From *Phil. Trans.*, vol. cliv., pp. 413–435, 1864)

INTRODUCTION

1. THE recent discovery by Kirchhoff of the connection between the dark lines of the solar spectrum and the bright lines of terrestrial flames, so remarkable for the wide range of its application, has placed in the hands of the experimentalist a method of analysis which is not rendered less certain by the distance of the objects the light of which is to be subjected to examination. The great success of this method of analysis, as applied by Kirchhoff to the determination of the nature of some of the constituents of the sun, rendered it obvious that it would be an investigation of the highest interest, in its relations to our knowledge of the general plan and structure of the visible universe, to endeavour to apply this new method of analysis to the light which reaches the earth from the fixed stars. Hitherto the knowledge possessed by man of these immensely distant bodies has been almost confined to the fact that some of them, which observation shows to be united in systems, are composed of matter subjected to the same laws of gravitation as those which rule the members of the solar system. To this may be added the high probability that they must be self-luminous bodies analogous to our sun, and probably in some cases even transcending it in brilliancy. Were they not self-luminous, it would be impossible for their light to reach us, from the enormous distances at which the absence of sensible parallax, in the case of most of them, shows they must be placed from our system.

The investigation of the nature of the fixed stars by a prismatic analysis

of the light which comes to us from them, however, is surrounded with no ordinary difficulties. The light of the bright stars, even when concentrated by an object-glass or speculum, is found to become feeble when subjected to the large amount of dispersion which is necessary to give certainty and value to the comparison of the dark lines of the stellar spectra with the bright lines of terrestrial matter. Another difficulty, greater because it is in its effect upon observation more injurious, and is altogether beyond the control of the experimentalist, presents itself in the ever-changing want of homogeneity of the earth's atmosphere, through which the stellar light has to pass. This source of difficulty presses very heavily upon observers who have to work in a climate so unfavourable in this respect as our own. On any but the finest nights the numerous and closely approximated fine lines of the stellar spectra are seen so fitfully that no observations of value can be made. It is from this cause especially that we have found the inquiry, in which for more than two years and a quarter we have been engaged, more than usually toilsome; and indeed it has demanded a sacrifice of time very great when compared with the amount of information which we have been enabled to obtain.

2. Previously to January 1862, in which month we commenced these experiments, no results of any investigation undertaken with a similar purpose had been published. With other objects in view, two observers had described the spectra of a few of the brighter stars—viz. Fraunhofer in 1823,* and Donati, whose memoir, “Intorno alle Strie degli Spettri stellari,” was published in the *Annali del Museo Fiorentino* for 1862.

Fraunhofer recognised the solar lines D, E, *b*, and F in the spectra of the Moon, Venus, and Mars; he also found the line D in Capella, Betelgeux, Procyon, and Pollux; in the two former he also mentions the presence of *b*. Castor and Sirius exhibited other lines. Donati’s elaborate paper contains observations upon fifteen stars; but in no case has he given the positions of more than three or four bars, and the positions which he ascribes to the lines of the different spectra relatively to the solar spectrum do not accord with the results obtained either by Fraunhofer or by ourselves. As might have been anticipated from his well-known accuracy, we have not found any error in the positions of the lines indicated by Fraunhofer.

3. Early in 1862 we had succeeded in arranging a form of apparatus in which a few of the stronger lines in some of the brighter stars could be seen. The remeasuring of those already described by Fraunhofer and Donati, and even the determining the positions of a few similar lines in other stars, however, would have been of little value for our special object, which was to ascertain, if possible, the constituent elements of the different stars. We therefore devoted considerable time and attention to the perfecting of an apparatus which should

* Gilbert’s “Annalen,” vol. lxxiv., p. 374.

possess sufficient dispersive and defining power to resolve such lines as D and b of the solar spectrum. Such an instrument would bring out the finer lines of the spectra of the stars, if in this respect they resembled the sun. It was necessary for our purpose that the apparatus should further be adapted to give accurate measures of the lines which should be observed, and that it should also be so constructed as to permit the spectra of the chemical elements to be observed in the instrument simultaneously with the spectra of the stars. In addition to this, it was needful that these two spectra should occupy such a position relatively to each other, as to enable the observer to determine with certainty the coincidence or non-coincidence of the bright lines of the elements with the dark lines in the light from the star.

4. Before the end of the year 1862 we had succeeded in constructing an apparatus which fulfilled part of these conditions. With this some of the lines of the spectra of Aldebaran, α Orionis, and Sirius were measured; and from these measures diagrams of these stars, in greater detail than had then been published, were laid before the Royal Society in February 1863. After the note was sent to the Society, we became acquainted with some similar observations on several other stars by Rutherford, in *Silliman's Journal* for 1863. About the same time figures of a few stellar spectra were also published by Secchi. In March 1863 the Astronomer Royal presented a diagram to the Royal Astronomical Society, in which are shown the positions of a few lines in sixteen stars.

Since the date at which our Note was sent to the Royal Society our apparatus has been much improved, and in its present form of construction it fulfils satisfactorily several of the conditions required.*

5. The satisfactory performance of this apparatus is proved by the very considerable dispersion and admirably sharp definition of the known lines in the spectra of the sun and metallic vapours. When it is directed to the sun, the line D is sufficiently divided to permit the line within it, marked in Kirchhoff's map as coincident with nickel, to be seen. The close groups of the metallic spectra are also well resolved.

When this improved apparatus was directed to the stars, a large number of fine lines was observed, in addition to those that had been previously seen. In the spectra of all the brighter stars which we have examined, the dark lines appear to be as fine and as numerous as they are in the solar spectrum. The great breadth of the lines in the green and more refrangible parts of Sirius and some other stars, as seen in the less perfect form of apparatus which was first employed, and which band-like appearance was so marked as specially to distinguish them, has, to a very great extent, disappeared; and though these lines are still strong, they now appear, as compared with the strongest of the

* See Section I., "Observatory and Instruments."

solar lines, by no means so abnormally broad as to require these stars to be placed in a class apart. No stars sufficiently bright to give a spectrum have been observed to be without lines. The stars admit of no such broad distinctions of classification. Star differs from star alone in the grouping and arrangement of the numerous fine lines by which their spectra are crossed.

6. For the convenience of reference and comparison, a few of the more characteristic lines of twenty-nine of the elements were measured with the instrument. These were laid down to scale, in order to serve as a chart, for the purpose of suggesting, by a comparison with the lines measured in the star, those elements the coincidence of the lines of which with stellar lines was probable.

For the purpose of ensuring perfect accuracy in relative position in the instrument between the star-spectrum and the spectrum to be observed simultaneously with it, the following general method of observing was adopted:—The flame of a small lamp of alcohol, saturated with chloride of sodium, was placed centrally before the object-glass of the telescope, so as to furnish a sodium-spectrum. The sodium-spectrum was then obtained by the induction spark, and the mirror *f*, fig. 1, p. 9, was so adjusted that the components of the double line D, which is well divided in the instrument, should be severally coincident in the two spectra. The lamp was then removed, and the telescope directed to the sun, when Fraunhofer's line D was satisfactorily observed to coincide perfectly with that of sodium in the induction-spark. Having thus ascertained that the sodium lines coincided in the instrument with the solar lines D, it was of importance to have assurance from experiment that the other parts of the solar spectrum would also accurately agree in position with those corresponding to them in the spectrum of comparison. When electrodes of magnesium were employed, the components of the triple group characteristic of this metal severally coincided with the corresponding lines of the group *b*. C and F also agreed exactly in position with the lines of hydrogen; the coincidence of several of the principal lines of iron was also observed. The stronger of the Fraunhofer lines were measured in the spectra of the moon and of Venus, and these measures were found to be accordant with those of the same lines taken in the solar spectrum.

Before commencing the examination of the spectrum of a star, the alcohol-lamp was again placed before the object-glass of the telescope, and the correct adjustment of the apparatus obtained with certainty. The first observation was whether the star contained a double line coincident with the sodium line D. When the presence of such a line had been satisfactorily determined, we considered it sufficient in subsequent observations of the same star to commence by ascertaining the exact agreement in position of this known stellar line with the sodium line D.

Since from flexure of the parts of the spectrum apparatus the absolute reading of the micrometer might vary when the telescope was directed to stars differing greatly in altitude, the measure of the line in the star which was known to be coincident with that of sodium was always taken at the commencement and at the end of each set of measures. The distances of the other lines from this line, and not the readings of the micrometer, were then finally registered as the measures of their position; and these form the numbers given in the tables, from which the diagrams of the star-spectra have been laid down.

The very close approximation, not unfrequently the identity, of the measures obtained for the same line on different occasions, as well as the very exact agreement of the lines laid down from these measures with the stellar lines subsequently determined by a direct comparison with metallic lines the positions of which were known, have given the authors great confidence in the minute accuracy of the numbers and drawings which they have now the honour of laying before the Society.

OBSERVATIONS ON THE FIXED STARS

The number of fixed stars which we have, to a greater or less extent, examined amounts to nearly fifty. We have, however, concentrated our efforts upon three or four of the brighter stars, and two only of these have been mapped with any degree of completeness. These spectra are, indeed, as rich in lines as that of the sun, and even with these it may be advantageous to compare the spectra of additional metals when the season is again favourable. The few really fine nights that are available whilst the star is well situated for such observations, in respect of altitude and the time of sun-setting, necessarily make the *complete* investigation even of a single star the work of some years.

ALDEBARAN (α Tauri) (Plate XI., p. 60).—The light of this star is of a pale red. When viewed in the spectroscope, numerous strong lines are at once evident, particularly in the orange, the green, and the blue portions. The positions of about seventy of these lines have been measured, and their places have been given in the table. Besides these, numerous other strong lines are visible, particularly in the blue, but they have not been measured, owing to the feebleness of the light; we have therefore not inserted them in the table or in the diagram. A similar remark is applicable also to the results of our examination of α Orionis and β Pegasi.

We have compared the spectra of sixteen of the terrestrial elements by simultaneous observation with the spectrum of Aldebaran, of course selecting those in which we had reason, from the observations, to believe coincidence

was most likely to occur. Nine of these spectra exhibited lines coincident with certain lines in the spectrum of the star. They are as follows :—sodium, magnesium, hydrogen, calcium, iron, bismuth, tellurium, antimony, and mercury.*

(1) *Sodium*.—The double line at D was coincident with a double line in the stellar spectrum.

(2) *Magnesium*.—The three components of the group at *b*, from electrodes of the metal, were coincident with three lines in the star-spectrum.

(3) *Hydrogen*.—The line in the red corresponding to C, and the line in the green corresponding to F in the solar spectrum, were coincident with strong lines in the spectrum of Aldebaran.

(4) *Calcium*.—Electrodes of the metal were used ; four lines in its spectrum were observed to coincide with four of the stellar lines.

(5) *Iron*.—The lines in the spectrum of this metal are very numerous, but not remarkable for intensity. There was a double line corresponding to E in the solar spectrum, and three other more refrangible well-marked lines coincident with lines in the star.

(6) *Bismuth*.—Four strong lines in the spectrum of this metal coincided with four in the star-spectrum.

(7) *Tellurium*.—In the spectrum of this metal also four of the strongest lines coincided with four in the spectrum of the star.

(8) *Antimony*.—Three of the lines in the spectrum of antimony were observed to coincide with stellar lines.

(9) *Mercury*.—Four of the brightest lines in the mercury-spectrum correspond in position with four lines of the star.

It must not be supposed that other lines in all the spectra of the elements above enumerated do not possess corresponding lines in the star-spectrum. Comparisons of this kind are extremely fatiguing to the eye, and are necessarily limited to the stronger lines of each spectrum. In no case, in the instances above enumerated, did we find any strong line in the metallic spectrum wanting in the star-spectrum, in those parts where the comparison could be satisfactorily instituted.

* On account of the necessarily restricted power of the small stellar spectroscope attached to my 8-inch achromatic telescope, the apparent coincidences of bright terrestrial lines with dark lines in the spectrum of a star might possibly not always represent true coincidences of position. Some of the strong stellar lines, apparently single, might not be really so, but under greater power be resolved into two or more closely adjacent lines, and the apparent coincidence would break down. In the case, however, of substances possessing spectra markedly characteristic—as, for example, the peculiar grouping of the lines of hydrogen and of iron, the double line of sodium, the triple character of the green line of magnesium, and some others—the determination of their presence in the stars could be accepted without reserve, as has been abundantly confirmed by subsequent observations.

One important object of this original spectroscopic investigation of the light of the stars and other celestial bodies, namely to discover whether the same chemical elements as those of our earth are present throughout the universe, was most satisfactorily settled in the affirmative ; a common chemistry, it was shown, exists throughout the visible universe. [1909.]

Seven other elements were compared with this star—viz. nitrogen, cobalt, tin, lead, cadmium, lithium, and barium. No coincidence was observed. With *nitrogen* three strong double lines were compared, with *cobalt* one strong single line and a double line, with *tin* five lines, with *lead* two strong lines, with *cadmium* three lines, with *barium* two of the strongest in the green, and with *lithium* the line in the orange, but were found to be without any strong lines in the star-spectrum corresponding with them. The positions of these several lines relatively to the star-spectrum are given in the diagram.

a ORIONIS (Betelgeux) (Plate XI., p. 60).—The light of this star has a decided orange tinge. None of the stars which we have examined exhibits a more complex or remarkable spectrum than this. Strong groups of lines are visible, especially in the red, the green, and the blue portions. In the blue comparatively few of these lines have been measured with accuracy; we have therefore not inserted them in the table or the diagram. We have measured the position of about eighty lines in the brighter portions of this spectrum.

In the interval between the Divisions 890 and 920 of the scale adopted in the diagram, is a shading as of fine lines. A fainter shading of the same character is observed between 990 and 1010, also from 1050 to 1069. A stronger similar shading occurs from 1145 to 1170, and from 1280 to 1300. A similar shaded band commences at 1420, and another at 1557.

The spectra obtained from sixteen elementary bodies were observed simultaneously with the spectrum of *a Orionis*. In five of these, viz. sodium, magnesium, calcium, iron, and bismuth, lines corresponding with certain stellar lines were found to exist.

(1) *Sodium*.—The lines coincident with D are fainter in this star than in Aldebaran.

(2) *Magnesium*.—Decided group of three stellar lines coincident with the group at *b*.

(3) *Calcium*.—Four lines of this metal were on two different occasions seen to be coincident with four lines in the spectrum of the star.

(4) *Iron*.—The double line of this metal at E, and three other more refrangible bright lines, coincide with lines in the star-spectrum.

(5) *Bismuth*.—In the spectrum of this metal also four lines were found to coincide with four in the stellar spectrum.

Thallium.—The bright green line so characteristic of this metal appears to coincide with one of the lines seen in the star-spectrum; but this line may be due to calcium, since the small difference between the position of the thallium line and that of one of the calcium lines very close to it would not be distinguishable with the dispersive power of the apparatus employed.

In the spectra of the other elements which we compared with that of the star, no coincidences occur.

Hydrogen.—There is no line coincident with the red line C of hydrogen; but in the star are two strong lines, one on either side of the position of C: there is also no line coincident with F. It is strikingly confirmatory of this method of analysis, that in all the stars hitherto examined by us in which a line corresponding to C exists, that corresponding to F is also found. When F is absent, C is also wanting.*

In *nitrogen* three strong double lines were compared. In *tin* five lines, and in *lead* two bright lines were compared, but no coincidence was found.

Gold.—The strongest of the gold lines approximates closely in position to one in the spectrum of the star, but it is probably not coincident.

Three of the strong lines of *cadmium*, two of *silver*, four of *mercury*, two of *barium*, and one (the orange line) of *lithium* were observed to be not coincident with any of the lines visible in the star. In these comparisons, when barium was used, it was employed in the form of a nearly solid amalgam.

The opening of the slit was maintained at the same width (not more than the $\frac{1}{500}$ th of an inch) for all the observations, both with Aldebaran and α Orionis. In the case of the fainter star which follows, it was very slightly widened.

β PEGASI.—The colour of this star is a fine yellow. In the general arrangement of the groups, in the gradation of the strength of the lines composing the groups, and in the absence of the hydrogen lines, this spectrum, though much fainter, is closely analogous with the spectrum of α Orionis, as figured in the Plate.

This star was carefully observed on many different occasions; but the faintness of the star, and the unfavourable state of the atmosphere on many of the nights of observation, did not permit the same number of lines to be measured, nor allow a comparison with an equal number of terrestrial elements. From November 10, 1862, when twelve lines were observed, to the present year, we have scrutinised the star carefully.

Nine of the elements were compared with the spectrum of β Pegasi. Two of these, viz. *sodium* and *magnesium*, and perhaps a third, viz. *barium*, furnish spectra in which there are lines which coincide with lines in the spectrum of the star.

The spectra of *iron* and *manganese* were also compared with that of the star, but the state of the atmosphere prevented any certain conclusion.

The lines in the spectra of *nitrogen*, *tin*, and *mercury* were not coincident with any definite lines in the star-spectrum. Neither of the *hydrogen* lines corresponding to C and F was present.

At the end of the paper we have given a table of such measures of the lines in the spectrum of this star as we can depend upon. Although it appears to be as full of lines as either of the preceding stars, the observations are attended with great difficulty, owing to the insufficient amount of light.

* C and F were seen later in this star, see p. 78.

The absence in the spectrum of α Orionis, and also in the spectrum of β Pegasi, which so closely resembles it in character, of lines corresponding to those of hydrogen, is an observation of considerable interest. It is of the more importance since the lines C and F are highly characteristic of the solar spectrum and of the spectra of by far the larger number of the fixed stars to which our observations have been extended.*

These exceptions are further interesting as they seem to prove that the lines C and F are due to the luminous bodies themselves. Of this some doubt might be entertained, and it might be suspected that they are in some way due to our own atmosphere, if these lines were present in the spectra of *all* the stars without exception.

This absence of the lines corresponding to hydrogen is also the more entitled to consideration since it is so rare to find them wanting, amongst the considerable number of stellar spectra which we have observed.

SIRIUS.—The spectrum of this brilliant white star is very intense; but, owing to its low altitude, even when most favourably situated, the observation of the finer lines is rendered very difficult by the motions of the earth's atmosphere. For the present we do not give any details of our measures. The lines in the green and blue appeared in the less perfect form of spectroscope which we employed in the early part of 1863, of very great breadth, and were so figured in the diagram of the spectrum of this star given in our "Note" of February 1863. With our present instrument, possessing much greater dispersive power and a very narrow slit, these bands appear but little broader than F and G are at times seen in the solar spectrum. In February 1863 the breadth of the band corresponding to F measured $1\frac{1}{2}$ unit of the scale we then adopted; each unit corresponded to 15·5 units of our present scale. The micrometric measurement of this line in Sirius, in terms of our present scale, is only 3·7—that is, only about one-seventh of the breadth as seen with the wider slit and a dispersing arrangement having little more than one-third of the power of the present apparatus.

Three if not four elementary bodies have been found to furnish spectra in which lines coincide with those of Sirius—viz. sodium, magnesium, hydrogen, and probably iron.

(1) *Sodium*.—A double line in the star, though faint, coincides in position with the line of this metal.

(2) *Magnesium*.—Three lines in the star-spectrum coincide with the triple group of magnesium.

(3) *Hydrogen*.—Both the lines corresponding to F and C have intensely strong lines in the star-spectrum.

(4) *Iron*.—No direct comparison with this metal was made; but the cross

* Later, the hydrogen lines at C and F were seen in these stars, see p. 78.

wires having been set to a position corresponding with E of the solar spectrum, a faint line in the star was seen exactly to bisect the wires when the telescope was turned upon Sirius.

The whole spectrum of Sirius is crossed by a very large number of faint and fine lines.

It is worthy of notice that in the case of Sirius, and a large number of the white stars, at the same time that the hydrogen lines are abnormally strong as compared with the solar spectrum, all the metallic lines are remarkably faint.

On February 27, 1863, and on March 3 of the same year, when the spectrum of this star was caused to fall upon a sensitive collodion surface, an intense spectrum of the more refrangible part was obtained. From want of accurate adjustment of the focus, or from the motion of the star not being exactly compensated by the clock movement, or from atmospheric tremors, the spectrum, though tolerably defined at the edges, presented no indications of lines. Our other investigations have hitherto prevented us from continuing these experiments further; but we have not abandoned our intention of pursuing them.

α LYRÆ (Vega).—This is a white star having a spectrum of the same class as Sirius, and as full of fine lines as the solar spectrum. Many of these we have measured, but our investigation of this star is incomplete.

We have ascertained the existence, in the stellar spectrum, of a double line at D corresponding to the lines of *sodium*, of a triple line at b coinciding with the group of *magnesium*, and of two strong lines coincident with the lines of *hydrogen* C and F.

CAPELLA.—This is a white star with a spectrum closely resembling that of our sun. The lines are very numerous; we have measured more than twenty of them, and ascertained the existence of the double *sodium* line at D, but we defer giving details until we have completed our comparison with the spectra of other metals.

From this star we obtained (on February 27, 1863) a photograph of the more refrangible end of the spectrum; but the apparatus was not sufficiently perfect to exhibit any stellar lines.

ARCTURUS (α Boötis).—This is a red star the spectrum of which somewhat resembles that of the sun. In this also we have measured upwards of thirty lines, and have ascertained the existence of a double *sodium* line at D; but our comparisons with other metallic spectra are not yet complete.

POLLUX.—In the spectrum of this star, which is rich in lines, we have measured twelve or fourteen, and have observed coincidences with the lines of *sodium*, *magnesium*, and probably of *iron*. At any rate there is a line which we believe occupies the position of E in the solar spectrum.

α CYGNI and PROCYON are both full of fine lines. In each of these spectra we observed a double line coincident with the *sodium D*.

The following stars have also been observed : numerous lines are seen in the spectrum of each ; and in some, several of the lines were measured ; but we have not instituted any comparisons with the metallic spectra as yet :—

Castor ; ϵ , ζ , and η *Ursæ majoris* ; α and ϵ *Pegasi* ; α , β , and γ *Andromedæ*, the last an interesting spectrum ; *Rigel*, a spectrum full of fine lines ; η *Orionis* ; α *Trianguli* ; γ and ϵ *Cygni* ; α , β , γ , ϵ , and η *Cassiopeiae* ; γ *Geminorum* ; β *Canis majoris* ; β *Canis minoris* ; *Spica* ; γ , δ , and ϵ *Virginis* ; α *Aquilæ* ; *Cor Caroli* ; β *Aurigæ* ; *Regulus* ; β , γ , δ , ϵ , ζ , and η *Leonis*.

GENERAL OBSERVATIONS

On the Colours of the Stars.—From the earliest ages it has been remarked that certain of the stars, instead of appearing to be white, shine with special tints ; and in countries where the atmosphere is less humid and hazy than our own, this contrast in the colour of the light of the stars is said to be much more striking. Various explanations of the contrast of colours, by Sestini and others, founded chiefly on the difference of the wave-lengths corresponding to the different colours, have been attempted, but as yet without success. Probably in the constitution of the stars as revealed by spectrum analysis, we shall find the origin of the differences in the colour of stellar light.*

Since spectrum analysis shows that certain of the laws of terrestrial physics prevail in the sun and stars, there can be little doubt that the immediate source of solar and stellar light must be solid or liquid matter maintained in an intensely incandescent state, the result of an exceedingly high temperature. For it is from such a source alone that we can produce light even in a feeble degree comparable with that of the sun.

The light from incandescent solid and liquid bodies affords an unbroken spectrum containing rays of light of every refrangibility within the portion of the spectrum which is visible. As this condition of the light is connected with

* In connection with this subject we quote the following passage from Smyth's "Speculum Hartwellianum," 4to, 1860, p. 315: "Sir David Brewster observes that there can be no doubt that in the spectrum of every coloured star certain rays are wanting which exist in the solar spectrum ; but we have no reason to believe that these defective rays are absorbed by any atmosphere through which they pass. And in recording the only observation perhaps yet made to analyse the light of the coloured stars, he says, 'In the orange-coloured star of the double star ζ Herculis, I have observed that there are several defective bands. By applying a fine rock-salt prism, with the largest possible refracting angle, to this orange star, as seen in Sir James South's great achromatic refractor, its spectrum had the annexed appearance [in the *Campden Hill Journal*], clearly showing that there was one defective band in the red space and two or more in the blue space. Hence the colour of the star was orange, because there was a greater defect of blue than of red rays.'"

the state of solidity or liquidity, and not with the *chemical* nature of the body, it is highly probable that the light when first emitted from the photosphere, or light-giving surface of the sun and of the stars, would be in all cases identical.

The source of the difference of colour, therefore, is to be sought in the difference of the constituents of the investing atmospheres.* The atmosphere of each star must vary in nature as the constituents of the star vary; and observation has shown that the stars do differ from the sun and from each other in respect of the elements of which they consist. The light of each star, therefore, will be diminished by the loss of those rays which correspond in refrangibility to the bright lines which the constituents of each atmosphere would, in the incandescent state, be capable of emitting. In proportion as these dark lines preponderate in particular parts of the spectrum, so will the colours in which they occur be weaker, and consequently the colours of other refrangibilities will predominate.

Of this the spectrum of α Orionis affords a good example. The green and blue parts of the spectrum are comparatively dark, from the numerous and close groups of dark lines. In the orange they are less strong. Hence it might be anticipated that the light of the star would be characterised by "an orange tinge," as noted by Smyth. β Pegasi is described by Smyth as "deep yellow"; and the appearance exhibited by its spectrum, which closely resembles that of α Orionis, though much fainter, supports the same view.

Aldebaran is recorded by Smyth as of a "pale rose tint." In the spectrum of this star, with the exception of the hydrogen line C, there are but few strong lines in the red, whilst the orange portion is considerably subdued by dark lines, which are less numerous in the green and blue. Sirius, on the contrary, is "brilliant white" (Smyth); and the continuous brightness of the spectrum, with the exception of five strong lines, is, as compared with Aldebaran and α Orionis, unaffected by the dark lines which cross it. The spectrum is indeed crowded with numerous fine lines; but the intensity of these lines is extremely feeble as contrasted with those of the stars just mentioned. It may be that the length of the stellar atmosphere through which the light passes is less, relatively to the intensity of radiation from the photosphere, and so is insufficient to produce lines of the same degree of blackness as would be produced if the atmosphere were denser. The great intensity, however, of the light of Sirius would rather lead to the conclusion that the atmosphere of vapours is itself highly incandescent. If so, might it

* The presence in the atmospheres of Aldebaran and α Orionis of metals, such as iron, which require an exceedingly high temperature to convert them into vapour, renders untenable the supposition, which might otherwise have been entertained, that the orange and red tints of the light of these stars might be due to an inferior degree of incandescence of the photosphere as compared with the temperature of the stars the light of which is white.

not to some extent replace with its own light, the light which it has absorbed from the photosphere behind it? It matters little, however, for the present purpose, whether or not either of these suppositions be adopted. There is at all events a most striking difference between the effect on the colour of the star of the closely grouped and very dark lines in the green and blue portions of the spectrum of α Orionis and of the corresponding portion of the spectrum of Sirius, in which the dark lines are faint and wholly unequal to produce any noticeable subduing of the blue and green rays.

We have not yet had an opportunity of testing by experiment whether this hypothesis of the origin of the colours of the light of the stars is also applicable to the remarkable exceptional class of stars the light of which is of a decided green, blue, or violet colour. Such stars are usually very small, and they are always so closely approximated to other more brilliant stars, that it is scarcely possible, with the apparatus which we employ, to obtain separate images of the two spectra: and even were such separation easily practicable, the light of the strongly coloured star is usually so feeble that its satisfactory prismatic analysis would be a matter of great difficulty.

[One of the objects proposed in the construction of the spectrum apparatus with which the additional observations on Jupiter, Saturn, and Mars were made, and which has been described, was to make it available for the prismatic observation of some double and multiple stars.

Before commencing the observation of the spectra of the components of a double star, it is necessary that the position-angle of the stars should be approximatively known. The spectrum apparatus has then to be rotated upon the end of the telescope until the direction of the slit becomes perpendicular to a line joining the stars. When the instrument is in this position, the images of the stars are elongated by the cylindrical lens into two short lines of light parallel with the slit, and separated from each other by a small interval. If the telescope be now moved in a direction at right angles to that of the slit, either of the elongated stellar images can, at pleasure, be made to fall upon the slit and form its spectrum in the instrument. By adopting this method of observation, the spectra of the components of β Cygni were separately examined. These spectra, especially that of B, are so faint that the lines are seen with difficulty, and scarcely admit of being measured. Since, however, on account of the strongly contrasted colours of these stars, considerable interest attaches to a comparative examination of their spectra, we have represented in fig. 4 (p. 9) the appearances which these spectra present to the eye, though we have not yet measured the lines and bands in them. These figures must be regarded as eye-estimations only of the general features of the two spectra. The spectra contain, doubtless, many other lines; and the positions of the lines inserted in the drawings, with the exception of

b and D, were not measured, but only roughly estimated. The distinctive characteristics of these spectra are in accordance with the theory of the origin of the colours of the stars proposed in the foregoing paragraphs. In the case of both stars, the portions of the spectrum which correspond to the colours which are deficient in the light of the star are those which are most strongly shaded with bands of absorption. Thus in the spectrum of A, the light of which is yellow tinted with orange, the absorption is greatest in the violet and blue; for the strong lines in the orange and red, since they are narrow, would diminish in a much smaller degree the light of these refrangibilities. The yellow and part of the green are free from *strong* lines.

The light of the star B appears to us to be blue, though in some states of the atmosphere the star becomes greenish blue, green, and even greenish white. These changes are probably due to the comparatively greater absorptive action of the vapour in the air upon the more refrangible portions of the spectrum; in proportion to which absorption the other parts of the spectrum become relatively exalted, and thus predominate more or less in the eye.

This inequality of the absorptive action of the vapours of the atmosphere upon different parts of the spectrum becomes very evident if the eyepiece of the telescope be put out of focus (without the focus), so as to bring the blue and red rays to a focus in the centre of an expanded image of the star. In the case of B of β Cygni, the centre appears purple, surrounded with a margin of green. In proportion to the changes in the atmosphere by the passage of masses of vapour or thin cloud, will be the variations of these colours. The green becomes greener; but the blue and the violet are affected in a much greater degree, at times fading almost completely; then the colours resume their former tints and brightness. Several such changes may sometimes occur during one observation.

The spectrum B, observed under conditions of atmosphere in which the colour of the star was blue, was remarkable for the faintness of the orange and yellow portions compared with the rest of the spectrum. The diminished brightness of these parts appears to be produced by several groups of closely set fine lines, while towards the more refrangible limit of the spectrum a few strong lines separated by considerable intervals are seen.

The observation of this star, on account of the faintness of its spectrum, is so difficult and fatiguing to the eye that we have not been able to examine it more accurately or in greater detail.*

We have by the same method of observation examined the spectra of the components of α Herculis. The spectrum of A is remarkable for the great strength of the groups of lines in the green, blue, and violet; fainter bands

* For the photographic spectra of the components of β Cygni, and of α Herculis, see *Atlas*, p. 161, and Plates XI. and XII.

are visible in the yellow and orange, also two strong bands in the red. This arrangement of the bands of absorption agrees with the orange colour which strongly predominates in the light of this star.

B is bluish green in colour. The more refrangible portions of its spectrum are very bright in consequence of the absence of any strong bands. The yellow and the orange parts are crossed by several groups of lines.—[August 31, 1864.]

The suggestive fact that stars of these more highly refrangible colours are always observed in close contiguity with much brighter stars, generally of an orange or red tint, would afford countenance to the supposition that these exceptional colours are due to some special physical conditions essentially connected with the stellar systems of which they seem to form a part.

Arago* remarks: "Among the sixty or eighty thousand *isolated* stars, the positions of which are to be found in the catalogues of astronomers, there are none, I think, inscribed with any other indications in regard to colour than white, red, and yellow. The physical conditions which determine the emission of blue and green light appear, then, to exist only in *multiple* stars."

These stars are without exception feeble in the intensity of their light. The explanation is not admissible, that the faint blue or violet light is due to a less intense incandescence of the radiating surface, since it is precisely these more refrangible rays which would be the first to fail as the temperature diminished, and upon this supposition the star should be dull red. It is of course to be supposed that in the process of gradual cooling some bodies which are less volatile than others would cease to exist in the atmosphere at an earlier period than others, or that they might enter into new combinations more readily than others, and so modify the tint of the light emitted.

The existence around these blue stars of an extended atmosphere of "fog" will not explain the absorption of the *less* refrangible portion of the luminous spectrum.†

These spectrum observations are not without interest also when viewed in connection with the *nebular hypothesis* of the cosmical origin of the solar system and fixed stars. For if it be supposed that all the countless suns which are distributed through space, or at least those of them which are bright to us, were once existing in the condition of nebulous matter, it is obvious that, though certain constituents may have been diffused throughout its mass, yet the composition of the nebulous material must have differed at different points; otherwise, during the act of agglomeration, each system must have collected and condensed equal proportions of similar materials from the mass

* "Popular Astronomy," translated by Smyth and Grant, vol. i., p. 295.

† For my later work on the spectra of double stars, see "Atlas of Representative Stellar Spectra," p. 157, and Plates XI. and XII., and p. 99 of this volume. (1909.)

around. It cannot be supposed that similarity in physical properties has caused the association of the different elements: we find, for example, some of the least volatile of the metals, such as iron, associated with highly volatile elements, such as mercury and tellurium, in the same star.

If we may so say, there seems to be some analogy between this irregular distribution of the elements in different centres in space, and the manner in which the components of the earth's crust are distributed. Upon the earth there are certain very generally diffused elements, such as oxygen, hydrogen, carbon, silicon, iron, aluminium, and calcium, which occur in all parts; whilst there are others which, like silver, tin, lead, and other metals, are accumulated at particular points only. Whatever may have been the physical causes which may have produced this separation, we see abundant evidence of the advantage of this distribution in their application to the purposes of man—smallness in relative amount being compensated for by the accumulation of the material in denser deposits, which allow of their comparatively easy extraction to supply the wants of mankind. If this arrangement be admitted as designed in the case of the earth, is it going beyond the limits of fair deduction to suppose that, were we acquainted with the economy of those distant globes, an equally obvious purpose might be assigned for the differences in composition which they exhibit? *

The additional knowledge which these spectrum observations give us of the nature and of the structure of the fixed stars seems to furnish a basis for some legitimate speculation in reference to the great plan of the visible universe, and to the special object and design of those numerous and immensely distant orbs of light.

The closely marked connection, in similarity of plan and mode of operation, in those parts of the universe which lie within the range of experiment, and so of our more immediate knowledge, renders it not presumptuous to attempt to apply the process of reasoning from analogy to those parts of the universe which are more distant from us.

Upon the earth we find that the innumerable individual requirements which are connected with the present state of terrestrial activity are not met by a plan of operation distinct for each, but are effected in connection with the special modifications of a general method embracing a wide range of analogous phenomena. If we examine living beings, the persistence of unity of plan observable amidst the multiform varieties of special adaptation of the vertebrate form of life may be cited as an example of the unity of operation referred to. In like manner the remarkably wide range of phenomena which are shown to be reciprocally interdependent and correlative of each other, by the recent great extension of our knowledge in reference to the relation of the different varieties of force and their connection with molecular motion, exhibits

* See discussion in *Atlas*, p. 72. (1909.)

a similar unity of operation amidst the changes of the bodies which have not life.

The observations recorded in this paper seem to afford some proof that a similar unity of operation extends through the universe as far as light enables us to have cognisance of material objects. For we may infer that the stars, while differing the one from the other in the kinds of matter of which they consist, are all constructed upon the same plan as our sun, and are composed of matter identical, at least in part, with the materials of our system.

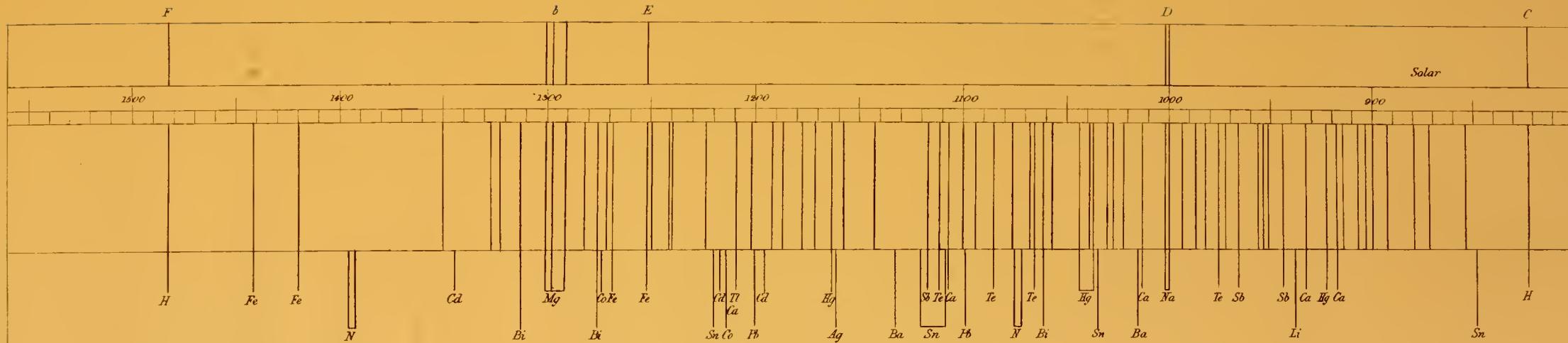
The differences which exist between the stars are of the *lower order*, of differences of *particular adaptation*, or special modification, and not differences of the *higher order* of distinct *plans of structure*.

There is therefore a probability that these stars, which are analogous to our sun in structure, fulfil an analogous purpose, and are, like our sun, surrounded by planets, which they by their attraction uphold, and by their radiation illuminate and energise. And if matter identical with that upon the earth exists in the stars, the same matter would also probably be present in the planets genetically connected with them, as is the case in our solar system.

It is remarkable that the elements most widely diffused through the host of stars are some of those most closely connected with the constitution of the living organisms of our globe, including hydrogen, sodium, magnesium, and iron. Of oxygen and nitrogen we could scarcely hope to have any decisive indications, since these bodies have spectra of different orders. These forms of elementary matter, when influenced by heat, light, and chemical force, all of which we have certain knowledge are radiated from the stars, afford some of the most important conditions which we know to be indispensable to the existence of living organisms such as those with which we are acquainted. On the whole we believe that the foregoing spectrum observations on the stars contribute something towards an experimental basis on which a conclusion, hitherto but a pure speculation, may rest—viz. that at least the brighter stars are, like our sun, upholding and energising centres of systems of worlds adapted to be the abode of living beings.*

* It will be obvious to every reader of my subsequent papers that the main line of argument on the concluding page of the preceding paper, written in 1864, even a short time after that date, no longer represented my attitude towards the doctrine, then novel, of evolution in organic as well as in inorganic nature. I have thought it best to allow the passage to remain unaltered, partly for the reason that the views expressed were fully shared by Dr. W. Allen Miller, whose name is associated with mine in that paper, and partly as showing how unfavourable for a free attitude of mind is early dogmatic teaching under the sacred sanction of religion. During the next two years my mind had so far freed itself from the dogmatic fetters of my early theological education that, in concluding my lecture before the British Association for the Advancement of Science in 1866, I was careful to say: "Our views of the universe are undergoing important changes; let us wait for more facts with minds unfettered by any dogmatic theory, and therefore free to receive the obvious teaching, whatever it may be, of new observations." (1909.)

ALDEBARAN.



α ORIONIS.

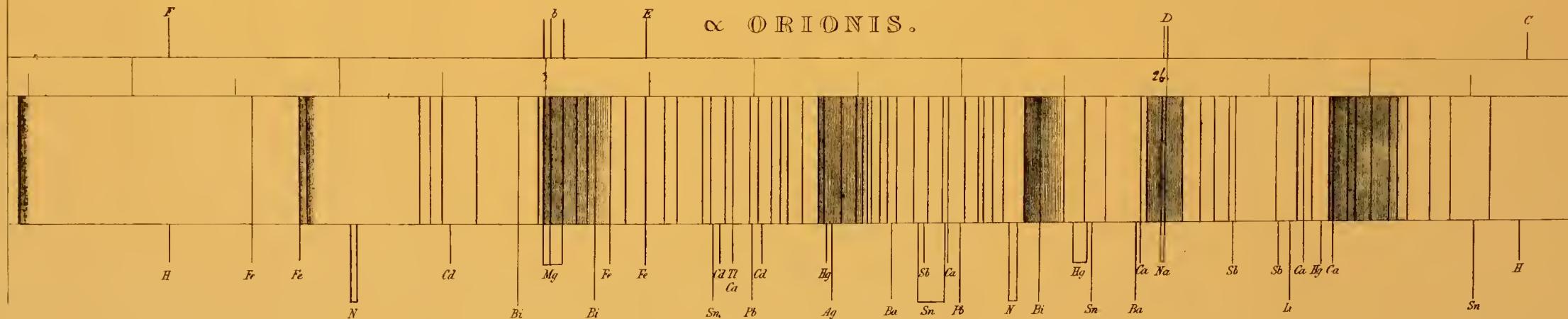


TABLE OF STELLAR SPECTRA

Aldebaran.			α Orionis.		β Pegasi.	
822·5	H	1107	840	1139·5	896	
855·5		1112	860	1144	923	
872·5		1117·5	870	1145·5	1000	}Na
880		1143 ^d	881	1148	1002	
893·5		1158	887	1151	1014	
900		1164 Hg	890	1158·5	1165	
903·5		1171·5	899	1167	1220	
907·5		1178	911	1169·5	1276·5	
915		1187	918 Ca	1176·5	1291·5	
918	Ca	1192	920	1183·5	1297·5	Mg
923	Hg	1202	929	1187	1300·5	
933	Ca	1210	933 Ca	1191·5	1350·5	
945·5	Sb	1224·5	936	1198	1392·5	
951·5		1240	946	1201·5	1425	
954·5		1241·5	966	1210 Te	1515	
956		1250	968·5	1214	1732	
966·5	Sb	1252 Fe	976	1220·5	1835	
972·5		1269·5 Fe	983	1225		
976	Te	1272	992	1237		
982		1277 Bi	1000 } Na	1243		
986·5		1282	1002 }	1252 Fe		
993		1291·5	1010·5	1262		
1000	} Na	1297·5	1013 Ca	1269·5 Fe		
1002	}	1300·5	1030	1277 Bi		
1013	Ca	1314 Bi	1040	1280·5		
1023		1323	1050·5	1285·5		
1028		1328	1062 Bi	1291·5		
1031		1351	1069·5	1297·5	Mg	
1036·5	Hg	1420 Fe	1079·5	1300·5		
1040		1442·5 Fe	1085·5	1303		
1044	Hg	1483 H	1090	1314 Bi		
1058			1091·5	1334		
1062	Bi		1099	1350		
1067	Te		1105 Ca	1356		
1076			1109·5	1361		
1086·5	Te		1116·5	1416		
1095			1123·5	1420 Fe		
1100			1132	1442·5 Fe		
1105	Ca		1135·5	1557		

NOTE ON THE PHOTOGRAPHIC SPECTRA OF STARS.

(From *Proc. Roy. Soc.*, vol. xxv., p. 445, 1876)

IN the year 1863 Dr. Miller and myself obtained the photograph of the spectrum of Sirius.

"On January 27, 1863, and on March 3 of the same year, when the spectrum of this star (Sirius) was caused to fall upon a sensitive collodion surface, an intense spectrum of the more refrangible part was obtained. From want of accurate adjustment of the focus, or from the motion of the star not being exactly compensated by the clock movement, or from atmospheric tremor, the spectrum, though tolerably defined at the edges, presented no indications of lines. Our other investigations have hitherto prevented us from continuing these experiments further; but we have not abandoned our intention of pursuing them."*

I have recently resumed these experiments by the aid of the 18-inch speculum belonging to the Royal Society's telescope in my possession. Considerable delay has arisen from the necessity, for these observations, of a more uniform motion of the driving-clock. For this purpose Mr. Howard Grubb has successfully applied to the clock the control of a seconds pendulum in electric connection with a sidereal clock. This system works quite satisfactorily.

The prisms employed are made of Iceland spar, and the lenses of quartz. After an extensive trial of different photographic processes, preference has been given to dry plates.

The apparatus is so arranged that a solar or electric spectrum can be taken on the same plate, for the purpose of comparison, with the spectrum of the star. Spectra have been obtained of Sirius, Vega, Venus, the Moon, etc.

I do not purpose in this preliminary notice to describe in detail the arrangements of the special apparatus which has been constructed, nor to offer the results of the experiments in their present incomplete state to the Royal Society. Still I venture to hope that, even in this early stage of the inquiry,

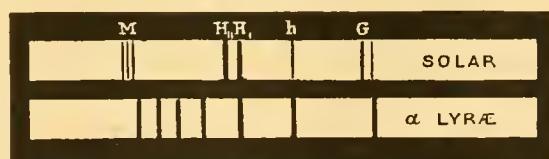


Fig. 13.

the enlarged copy of the spectrum of Vega (α Lyrae) which accompanies this note may not be regarded as altogether unworthy of attention.

* *Phil. Trans.*, 1864, p. 428.

After exposure to the light of Vega, the dry plate was allowed to remain in the instrument until the following morning, when a solar spectrum was taken upon it, through the half of the slit which had remained closed when the instrument was directed to the star.

The photograph shows seven strong lines, all of them slightly shaded at the sides. The two lines which are least refrangible coincide with two known lines of hydrogen in the solar spectrum.

It is expected, by means of an apparatus now in the course of construction, to obtain also any finer lines which may be present in the spectrum of this star, as well as to extend the photographic method to stars which are less bright.

I need not now refer to the many important questions in connection with which photographic observations of stars may be of value.

ON THE PHOTOGRAPHIC SPECTRA OF STARS

(From *Phil. Trans.*, 1880, Part ii., p. 669)

INTRODUCTION

In the year 1876 I presented to the Royal Society a preliminary note on the "Photographic Spectra of Stars."* I beg now to give an account in greater detail of my methods of work and of the photographs which I have obtained.

The importance of supplementing the observations by the eye of the spectra of stars, by photographs of the violet and ultra-violet portions of their spectra was so obvious, that as early as the year 1863 my friend Dr. W. Allen Miller and I made the attempt to obtain such photographs in addition to our eye-measures of star spectra.† With the apparatus then at our command we were not able to get any clear definition of lines, but a dark streak only upon the negative plate.

Other investigations which I then took up prevented me from resuming this line of work. I was also not encouraged to proceed further with photography at that time, as the clock-motion driving the telescope did not work with the accuracy that was necessary.

In the year 1875 Mr. Grubb replaced the driving-clock by a new one, in which there is a secondary control by means of a pendulum in electrical connection with a standard clock.‡ I am able to speak in terms of high praise of the performance of this new clock.

* *Proc. Roy. Soc.*, No. 176, 1876. Since the publication of my preliminary note, Professor H. Draper has written two notes on this subject, *American Journal of Science*, vol. xiii., Jan. 1877, and Nov. 27, 1879, p. 83.

† *Phil. Trans. R. S.*, 1864, p. 428. ‡ *Proceedings Royal Dublin Society*, April 21, 1879.

The early attempts at photography of the spectra of stars were made with the 8-inch refractor by Alvan Clark, then in my observatory. On receiving the new clock the refractor of the instrument lent to me by the Royal Society was dismounted and the Cassegrain telescope, with a metallic speculum of 18 inches diameter, was put in its place upon the equatorial stand. After many preliminary trials I adopted the following arrangements of the spectral apparatus and methods of work.

(For a description of the apparatus, see Section I., p. 12.)

At the early stages of these experiments I used wet collodion, but I soon found how great would be the advantages of using dry plates. Dry plates are not only more convenient for astronomical work, being always ready for use, but they possess the great superiority of not being liable to stains from draining and partial drying of the plates during the long exposures which are necessary even with the most sensitive plates. I then tried various forms of collodion emulsions, but finally gave up these in favour of gelatine plates, which can be made more sensitive. The development was sometimes by the ferrous oxalate process, at others by the ordinary pyrogallic method.

Positives were taken from the original negatives by placing the negative plate upon a similar dry plate and exposing to a gas flame for two or three seconds. Some of the negatives were enlarged, but it was found that a more satisfactory determination of doubtful points could be made from the original small negative or the positive taken from it when viewed under a microscope of low power than from an enlarged copy.

In the negatives the dark lines are represented by transparent spaces where the light has not acted. When these spaces are rather broad there may be some uncertainty in placing the wire of the micrometer exactly upon the middle of the transparent space. In the positives these spaces become dark lines, in which the middle part is usually the darkest. In nearly all cases, therefore, it was found desirable to confirm the measures of the lines made on the negatives by measures of the same lines in the positives taken from them.

In some cases the negatives were intensified by the usual methods, but they were not varnished.

SPECTRA FOR COMPARISON

It has been stated that one of the reasons for using a slit was, that spectra for comparison might be taken on the same plate.

The slit is furnished with two sliding shutters, each of which closes one-half of the length of the slit. When a star was photographed, one-half only of the slit was in use, the other half being closed by its shutter.

If the moon or one of the brighter planets was situated conveniently for

the purpose, the shutter which had remained closed was withdrawn, and the other shutter pushed in over the half of the slit which had been in use for the star. The telescope was then directed to the moon or planet. In this way the star's spectrum was obtained, together with that of solar light from the moon or planet.

If this method was not available, after exposure to the star's light the shutter was closed, and the apparatus with both shutters pushed in was allowed to remain until the next day, when by means of a small hand-mirror, direct sunlight, or light from the sky, was reflected through the hole in the large speculum, so as to fall upon the slit in the direction of the axis of the collimator.

More recently advantage was taken of those stars, the spectra of which had been compared with solar light. A spectrum of one of these stars was taken through the second half of the slit to serve as a fiducial spectrum of comparison. This method has the advantage of permitting the development of the plate to be performed the same evening.

The spectra of the planets were obtained on the same plate together with the lunar or solar spectrum. When, however, circumstances permitted, the plan employed by Dr. Miller and myself in our earlier eye observations was preferentially adopted. We wrote in 1864:—

"The length of the opening of the slit is much greater than the diameter of the telescopic image of the planet (Jupiter), even after elongation by the cylindrical lens. If therefore at the time of observation the light from the sky is sufficiently intense to form a visible spectrum, the spectrum of the sky is seen in the instrument, together with the spectrum of Jupiter, and much exceeding it in breadth. When the period is so chosen that the degree of illumination of the sky is suitable in proportion to the intensity of the light of Jupiter, the solar lines and those due to our atmosphere are well seen in close contiguity with the lines in the spectrum of Jupiter, and occupying exactly similar relative positions. The sky-spectrum is seen under precisely similar conditions of altitude and of state of atmosphere. To the light of Jupiter under these circumstances of observation is added the light reflected from the small area of sky immediately between the observer and the planet. This light is, however, too faint in proportion to that of Jupiter to become a source of error."*

Under similar circumstances, both shutters being withdrawn, spectra of the planets Jupiter and Venus were taken upon the broader spectrum of the sky. The solar lines are thus strictly comparable with those of the planetary spectra, since they were photographed under the same conditions of altitude and of terrestrial atmosphere.

* *Phil. Trans.*, 1864, p. 422.

When it was desired to obtain spectra of terrestrial substances for comparison, the spectroscope, as a whole, was drawn out of the grooves which hold it in its place at the end of the telescope, and was then fixed upon a kind of optical bench, on which also slide two lenses of quartz, and an apparatus to hold electrodes and tubes. These are so arranged that an image of the spark or tube is formed upon the slit. In this way photographs were taken, which are comparable with those of the stars, and could serve for the purpose of comparison when any known line was common to both spectra to form a fiducial point of measurement. As all the stellar photographs contain the line H, calcic chloride or metallic calcium was introduced into the spark, and the line of calcium corresponding to H, was used for this purpose.

There would have been no serious difficulty in so arranging the electrodes that a spectrum of the induction spark should be taken immediately after the star upon the same plate, but in actual practice there was some inconvenience in this arrangement. Two spectra on the same plate were not found to be satisfactory for comparison unless the "back" containing the plate had remained in its place. If it was removed, some difficulty was found in replacing it with the necessary accuracy.

DETERMINATION OF WAVE-LENGTHS

The map of M. Cornu of the solar spectrum from λ to O,* together with M. Mascart's determinations of the wave-lengths of the lines of cadmium in the ultra-violet,† were used for the reduction of the measures to wave-lengths.

The photographic spectra of the brighter stars can be traced upon the plate from about b to beyond S, but in the accompanying map (p. 78) I have limited myself to the portion of the spectrum between the line of hydrogen (γ) near G and O in the ultra-violet.

An admirable wire micrometer by Dollond, attached to a microscope furnished with a 2-inch objective, was used to measure the photographs. The readings of the micrometer head give 2·947 hundredths of a revolution for each ·000001 mm. of wave-length at the position of H.

By means of photographs of the solar spectrum, and of those of the spectra of iron, cadmium, calcium, and magnesium, a curve on a sufficiently large scale was laid down on paper ruled in millimetres connecting the measures of the micrometer with the intervals of wave-length. Great care was taken by cross-measurements in different ways to make this curve as accurate as

* *Annales de l'École Normale*, 2^e série, tom. 3, pl. 1.

† Mascart's "Recherches sur la Détermination des Longueurs d'Onde," *Annales de l'École Normale*, tom. 4, p. 1; also Cornu's "Détermination des Longueurs d'Onde des Radiations très réfrangibles du Magnésium, du Cadmium, du Zinc, et de l'Aluminium," *Archives des Sciences physiques et naturelles*, 15 juillet, 1879.

possible. The positions of the lines as determined in wave-lengths were afterwards confronted with solar lines by actual measurement under the microscope. I do not think the probable error of the determination in wave-lengths exceeds in any case ± 2 ten-millionths of a millimetre. For most of the lines I think it is less than half of this amount.

RESULTS

It need hardly be mentioned that only nights of great atmospheric clearness are suitable for stellar photography. The unusual prevalence of unfavourable weather during the time this work has been in hand has greatly limited the number of successful photographs I have been able to obtain. The remarkable circumstance of the apparent absence of the line K in one of my earlier photographs of Sirius made me select, in the first instance, other stars belonging to the same class.

In the accompanying map (p. 78) I have given of this class of stars the spectra of Sirius, Vega (α Lyrae), α Cygni, α Virginis, η Ursæ Majoris, and α Aquilæ, and representing a different class of stars the spectrum of Arcturus. In addition to these stars I have obtained photographs of β Pegasi, Betelgeux, Capella, α Herculis, and α Pegasi; but as these are more or less incomplete, in consequence of the unfavourable state of the atmosphere when they were taken, I prefer to reserve any description of their spectra for the present.

I have obtained good spectra of the planets Venus and Jupiter, taken together with a broader spectrum of daylight for comparison, and also of Mars.

Numerous photographs of limited areas of the moon's surface have been taken under different conditions of illumination, and also of the Moon during a partial eclipse of that body.

Besides the above objects there are several directions in which celestial spectrum photography could doubtless be applied with great advantage. One of these, which the bad weather alone has prevented me from attempting, was to supplement my former eye observations of the spectra of gaseous nebulæ by photography. As the light of these bodies is distributed among a few lines only, it seems by no means hopeless to obtain on the very sensitive gelatine plates which may now be made, photographs of any lines which may exist in the violet and ultra-violet portions of their spectra.

Another class of bodies to which the application of photography might give us much new knowledge are comets. The form of apparatus described would make it possible to obtain photographic spectra of the light from different parts of these bodies.

We may entertain some hope from photographic spectra of obtaining information of the condition of things under which the increase and diminution

of light occur in those stars which are periodically variable. It is not improbable that modifications may be discovered in the photographic portion of the spectrum, even when none are seen by the eye.

This same form of apparatus, with some obvious modification, would be useful in obtaining photographic spectra of the different portions of a sun-spot.

The photographic method may also be of use in the determination of the relative motion of two stars in the line of sight. The photographs I have obtained of the spectra of two stars on the same plate do show a very small relative shift; but in an inquiry of so great delicacy some special arrangements, which I need not here describe, would be necessary to ensure the photographs from some causes of possible minute instrumental displacement. Also photographic spectra of opposite limbs of the sun on the same plate may give evidence of the sun's rotation.

WHITE STARS.—SIRIUS, VEGA (α LYR.E), α AQUIL.E, α VIRGINIS, α CYGNI,
 α VIRGINIS

The photographic spectra of all these stars possess very strong characteristic features in common; indeed, the differences between their spectra must be regarded as modifications of a typical spectrum common to the whole class.

In our eye observations of stars of this class, Dr. W. Allen Miller and myself called attention to the intensely strong lines of hydrogen corresponding to C and F. Under favourable conditions of atmosphere we were able to see also, in stars of this class, very fine lines corresponding to the principal lines of sodium, magnesium, and iron, though in some of these stars the least refrangible line only of b was seen. We remarked of these stars: "It is worthy of notice that in the case of Sirius and a large number of white stars, at the same time that the lines of hydrogen are abnormally strong as compared with the solar spectrum, all the metallic lines are very faint."*

The photographs present a spectrum of twelve very strong lines (of these seven were given in my preliminary note). Beyond these lines a strong continuous spectrum can be traced as far as S, but without any further indication of lines. The least refrangible of these lines is coincident with the line (γ) of hydrogen near G. The next line in order of greater refrangibility agrees in position with h of the solar spectrum. The third line is H. K, if present at all, is thin and inconspicuous.† The nine lines which follow do not appear to

* *Phil. Trans.*, 1864, pp. 427–429.

† In 1876, Mr. Lockyer suggested that photographs of the spectra of the brighter stars might show modifications of this character of the lines of the calcium spectrum, and that such modifications would confirm his views as to the dissociation of this substance (*Proc. Roy. Soc.*, No. 168, 1876). Mr. Lockyer gives a fuller statement of his views on this and other points in connection with the different classes of the stars in *Proc. Roy. Soc.*, December 1878 (see fig. 50, p. 437).

be coincident with any of the stronger lines of the solar spectrum. These lines appear to be common to all the stars of this class, though it may be that some of the more refrangible lines are sometimes absent.

For the sake of convenience of reference I have distinguished these nine lines by the letters of the Greek alphabet in the order of their refrangibility.

I would wish to call attention to the remarkable arrangement in position in the spectrum of these lines. As the refrangibility increases the lines diminish in breadth, and the distance between any two adjacent lines is less. The group possesses a distinctly symmetrical character. The suggestion presents itself whether these lines are not intimately connected with each other, and present the spectrum of one substance.* It is also of importance to notice that

* [There is a high probability that this substance is hydrogen. The two lines in the visible part of the spectrum C and F forming part of the same group belong to hydrogen. Also, as stated above, the first two lines of the photographic group correspond to the line of hydrogen near G and to that at the position of h . Dr. H. W. Vogel has called my attention to a paper of his "On the Spectrum of Hydrogen" in the *Monatsbericht der Königl. Akademie der Wissenschaften zu Berlin*, July 10, 1879. Among other lines he gives the following, which agree in position with four of the typical lines :

Vogel's numbers.	My numbers.
λ 3968	λ 3968 H
3887	3887.5 α
3834	3834 β
3795	3795 γ

Dr. Vogel says in his letter (February 18, 1880): "In one of my last photographs I have another line λ 3769, your next line is 3767.5." Later, in 1886, Cornu succeeded in photographing the complete set of hydrogen lines in his laboratory. *Journal de Physique*, t. v., p. 341.

On January 24, 1880, I received the following note from Mr. Johnstone Stoney, F.R.S. :

"There can remain very little doubt that your typical lines are due to hydrogen. The evidence of their all being members of one physical system is made very plain when their positions are plotted down as in the following diagram, for it there becomes more conspicuous that they lie on, or very near, a definite curve, which could not happen by chance."

This question of whether they lie actually on, or only near, a definite curve is, if I mistake not, of very great significance in the theory. If they lie *on* a curve obeying any exact mathematical law, their connection must, I think, be attributed to their corresponding to the *consecutive* partial tones of some vibrating system (like those of an elastic rod or bell, for example). If, on the other hand, they lie near but not on the curve, this circumstance would support the hypothesis (which seems to accord with other facts) that the visible lines are members of harmonic series, most of the members of which are invisible, those only being

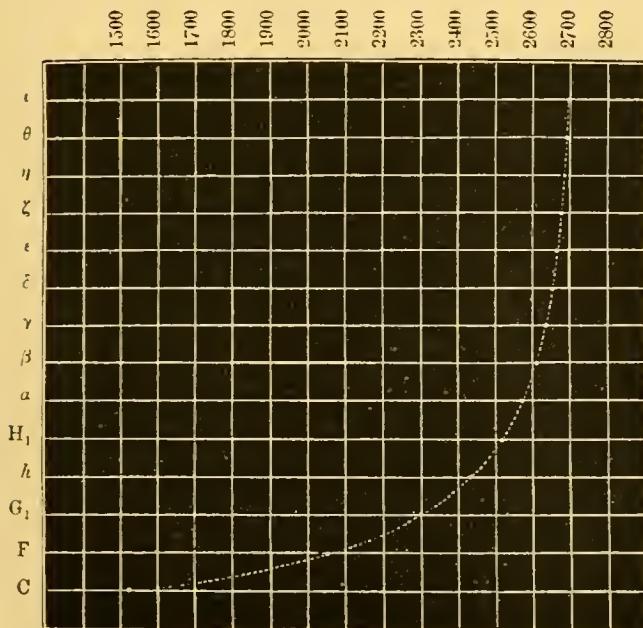


Fig. 14.

the spectrum does not end with the group. Beyond the last line, between M and N, the continuous spectrum runs on far beyond S in the ultra-violet. The wave-lengths of these lines will be found under Vega. The spectrum of Vega may be taken conveniently as typical of the whole class of white stars, so that the distinctive features of the other stars of this class may be regarded as modifications or departures from this common typical form. There are principally three directions in which the changes take place:

1. In the breadth and greater or less marginal diffuseness of the typical lines.

seen whose positions chance nearly to fulfil a definite condition—a state of things which I have shown to exist in some acoustic arrangements, and which wherever it prevails exalts the intensity of the harmonics whose positions nearly fulfil the requisite condition.

To ascertain which of the foregoing alternatives is the true account of your typical lines, I converted the wave-lengths as you determined them into wave-frequencies (the reciprocals of the wave-lengths), and made the following table of their first and second differences. Assuming that the irregularities in the second differences cannot be referred to errors of observation, I think that the accuracy of your work gives evidence which must be accepted that the second alternative is the true one—viz. that the lines do not lie on but near a definite curve.

W.—Wave-length in air.

Δn .—First difference.

n.—Wave-frequency in air.

$\Delta^2 n$.—Second difference.

	W.	n.	Δn .	$\Delta^2 n$.
C	6562·1	1523·9		
F	4860·7	2057·3		
H _γ	4340·1	2304·1		
h	4101·2	2438·3	134·2	52·4
H _I	3968·1	2520·1	81·8	29·6
a	3887·5	2572·3	52·2	16·3
β	3834	2608·2	35·9	9·1
γ	3795	2635·05	26·8	7·5
δ	3767·5	2654·3	19·3	3·7
ε	3745·5	2669·9	15·6	4·5
ζ	3730	2681	11·1	2·1
η	3717·5	2690	9	1·8
θ	3707·5	2697·2	7·2	1
ι	3799	2703·4	6·2	

This so far goes to show that the typical lines are not consecutive members of one series, but the members of one or more series whose positions lie near the curve. This appears to be corroborated by finding that H_I and the hydrogen line near G are connected harmonically, these rays being exactly the 35th and 32nd harmonics of a vibration whose fundamental is $\frac{\tau}{72\cdot003}$ (τ being the time in which light travels a millimetre in air). In fact, taking their wave-frequencies in air, I find as follows, the differences being wholly insensible:—

	n by calculation.	n by ÅNGSTRÖM's observations.
For line near G	$32 \times 72\cdot003 = 2304\cdot096$	2304·09
" " H	$35 \times 72\cdot003 = 2520\cdot105$	2520·10

2. In the presence or absence of K, and if present in its breadth and intensity relatively to H.

3. In the number and distinctness of the other lines of the spectrum.

One of these modifications, which possesses great suggestiveness, consists of the absence or difference of character presented by the line K. In all the stars of this class this line is either absent or is very thin as compared with its appearance in the solar spectrum, at the same time that H remains very broad and intense. In the spectrum of Arcturus, a star which belongs to another class, which includes our sun, this line K has passed beyond the condition in which it occurs in the solar spectrum, and even exceeds the solar K in breadth and intensity.

The spectra of these stars may therefore be arranged in a continuous series, in which first we find this line to be absent. Then it appears as an exceedingly thin line. We then pass to another stage in which it is distinct and defined at the edges; in the solar spectrum it becomes broad and winged;

The remaining typical lines do not belong to either this series or that of which C, F, and λ are members; and to include them we must suppose two other motions at least to exist in hydrogen.

Possibly six of these lines may be harmonics of $\frac{\tau}{9.0572}$, for I find:

			Calculated.	Observed.	Outstanding differences.
α	284	\times	$9.0572 = 2572.2$	2572.3	+0.1
β	288	\times	$" = 2608.5$	2608.2	-0.3
γ	291	\times	$" = 2635.6$	2635.05	-0.55
δ	293	\times	$" = 2653.8$	2654.3	+0.5
ζ	296	\times	$" = 2680.9$	2681.0	+0.1
η	297	\times	$" = 2690.0$	2690.0	0

and possibly the others, viz.: ϵ , θ , and ι , may be harmonics of $\frac{\tau}{6.845}$, for

			Calculated.	Observed.	Outstanding differences.
ϵ	390	\times	$6.845 = 2669.6$	2669.9	+3
θ	394	\times	$" = 2696.9$	2697.2	+3
ι	395	\times	$" = 2703.8$	2703.4	-4

I do not attribute much weight to the last two series, for I fancy the computed positions of γ and δ are too divergent from your observed positions. The calculation puts these lines 1 degree of wave-frequency scale (= 1.4 degree of Ångström's scale) nearer together than your determination."

Mr. Lockyer, in a "Note on the Spectrum of Hydrogen" (*Proc. Roy. Soc.*, December 17, 1879), describes a line in his photographs of hydrogen coincident with H in the solar spectrum.

In many of my own photographs this line and also fine lines coincident with most of the typical lines are seen, but I reserve for the present any further description of my experiments. The line H in such stars as Vega must be ascribed, chiefly at least, to hydrogen. To what extent in cooler stars this line may be due also to calcium we do not know.—March 10, 1880.]

[Messrs. Dewar and Liveing state that the calcium line K is more easily reversed than the calcium line at H (*Proc. Roy. Soc.*, February 20, 1879). This fact should be considered in connection with the presence of a line of hydrogen at H in any explanation that may be attempted of the phenomena presented in the stars.—March 30, 1880.]

and lastly in Arcturus there is further progress in the same direction, and the line, now a broad band, exceeds in intensity H.

Now the lines H and K agree in position with two strong lines in the spectrum of calcium, and are therefore usually believed to be produced by the vapour of that substance. It was therefore of some interest to ascertain if any of the other strong lines of the typical spectrum were coincident in position with a pair of strong lines in the calcium spectrum at 3736·5 and 3705·5. The calcium line 3736·5 falls nearly half-way between ϵ and ζ . The stellar line θ is indeed very near the calcium line 3705·5, but does not coincide with it, its position being 3707·5.

I prefer in the present paper not to enter into any discussion of the physical conditions corresponding to these variations in the line K,* nor to many important suggestions which naturally present themselves when we study the modifications of what it is convenient to regard as the most typical form of spectrum. Do these modifications not represent some of the stages through which our sun has passed? I hope to supplement my eye observations of 1864 of the gaseous nebulae by photographs of the more refrangible parts of their spectra. Such photographs, taken together with those described in this paper, and combined with our knowledge of the visible spectra of these bodies, would help us probably to a better understanding of the typical changes in the order of time through which a star passes.

In the hope of throwing some light on these and other questions which suggest themselves, I have taken for comparison a number of terrestrial spectra under various physical conditions. As I am still pursuing this inquiry I prefer at present to reserve an account of this part of my work.

VEGA (α LYR.E)

The photographic exposure with sensitive gelatine plates was from 15 to 30 minutes. Recently, with more sensitive plates, these times have been reduced. The photographs of this star show with great distinctness the twelve strong typical lines. There is a thin line at the position of K. In one photograph of this star I suspected the presence of a very delicate line between the lines H and K, but as I cannot be sure of its existence I have not inserted this line in the map. The line, if present, would be about λ 3945. A circumstance of great importance is the entire absence of any lines in the spectrum beyond ι , λ 3698. The spectrum, which then becomes continuous,

* Professors Dewar and Liveing have permitted me to witness some of their experiments in which analogous changes of relative intensity of K to H occur in the *emission* spectrum of calcium. They are of opinion that these variations and similar changes in the absorption spectrum, such as those shown in the stars, naturally follow from the known laws of emission and absorption. They state that the line of calcium K is more easily reversed than the line at the position of H.

is strong, and extends beyond S in the ultra-violet. In solar photographs taken with the same apparatus the lines of this region are well defined for some distance beyond S, and therefore this abrupt cessation of lines cannot be referred to an instrumental cause. All the lines are broad, and winged at the edges. After H the lines become less intense, and also better defined in the order of refrangibility.

LINES

	W.L.		W.L.
H	4340		δ 3767'5
h	4101		ϵ 3745'5
H_1	3968		ζ 3730
K	3933	very thin.	η 3717'5
α	3887'5		θ 3707'5
β	3834		ι 3699
γ	3795		

SIRIUS

In the photographs of this star we have a spectrum very similar to that of α Lyrae. I am not able to detect any line at the position of K, but as the altitude of the star is low the definition in the photograph is not quite so good as that of Vega. It is probably due to this cause that I have not been able to be sure of any lines beyond δ . I incline to believe that they would be detected probably in a more perfect spectrum. It may be, however, that ϵ , ζ , η , θ , ι are really absent in the spectrum of Sirius.

LINES

	W.L.		W.L.
H	4340		α 3887'5
h	4101		β 3834
H_1	3968		γ 3795
K	probably absent.		δ 3767'5

[See Addendum.]

 η URSAE MAJORIS

The spectrum of this star is very similar to the typical spectrum of Vega. When the two spectra are seen together on the same plate it is at once perceived that the lines are rather less winged and broad than those of Vega. Eleven lines have been measured. The existence of a twelfth line ι is doubtful, and therefore I have not inserted it in the map. As to K, any suspicion of a line here is far too doubtful to justify its insertion. As the spectrum is beautifully defined in the photograph, I think there is a strong presumption that it is absent.

A strong continuous spectrum extends beyond S. In this star we may mark a first step in the direction of a spectrum containing fine lines in the photographic portion of the spectrum. Four fine lines are inserted in the map.

		LINES	
H	4340		β 3820 very thin.
	4087.5	thin and faint.	γ 3795
	4137.5	thin, but distinct.	δ 3767.5
<i>h</i>	4101		ϵ 3745.5
	4021	thin, distinct.	ζ 3730
H ₁	3968		η 3717.5
K		probably absent.	θ 3707.5
<i>a</i>	3887.5		<i>i</i> probably present.
β	3834		

a VIRGINIS

In this spectrum we find ourselves advancing towards a condition in which the twelve lines are narrower and defined at the edges. At the same time a greater number of fine lines have appeared. I suspect a thin line at the position of K, and I have indicated this probability by a dotted line in the map (p. 78). There is no doubt of line between H and K. In this spectrum I have not been able to measure lines beyond η , though the continuous spectrum is strong and extends to about S.

		LINES	
H	4340	α	3887.5
	4137.5 thin.	β	3834
	4120 thin.	γ	3816.1 thin
η	4101	δ	3795
	4022.5 thin.	ϵ	3767.5
	4004.5 thin.	ζ	3745.5
H ₁	3968	η	3730
	3944.5 thin.	θ	3717.5
K	3933 probably present as a thin line.	ι	doubtful
	3920 thin.		

α AQUILÆ

All the lines are narrower than in Vega, and are well defined at the edges. In this spectrum we have numerous lines, besides the twelve strong lines, and the spectrum may be regarded as changed considerably in the direction of stars of the solar type. The line K is now strong, though still inferior to H. Six lines have been measured in the spectrum beyond ι , and possibly there may be lines still more refrangible. In addition to these, seventeen fine lines have been measured between the strong typical lines.

LINES	
H	4230
	4172.5
	4131 } pair of lines.
	4120 }
h	4101
	4072
	4022.5
	4000 } pair.
	3997 }
H _I	3968
K	3933
	3915
a	3887.5
	3862.5
	3854
β	3834
	3807.5
	3795
	3767.5
	3757.5
	3745.5
	3730
	3717.5
	3707.5
	3698
	3690
	3677.5
	3656
	3654
	3637.5

α CYGNI

If we consider only the breadth of K and the narrowness and defined character of the lines, this spectrum is much altered in the direction of the solar type. On the other hand, few lines beyond the typical ones are present. The photograph is not strong, and I have not been able to measure the two most refrangible of the typical lines θ and ι .

LINES	
H	4340
h	4101
H _I	3968
K	3933 a strong line, nearly as strong as H _I .
a	3887.5
	3862.5
β	3834
γ	3795
δ	3767.5
	3757.5
ϵ	3745.5
ζ	3730
η	3717.5

ARCTURUS

In this spectrum we have to do with a different order of suns, and have now entered upon the solar class of stars. The line K is very broad and winged, more so than H, and is stronger than it is in the solar spectrum.

In the eye observations by Dr. Miller and myself we said: "This is a red star, the spectrum of which somewhat resembles that of the sun. In this we have measured upwards of thirty lines and ascertained the existence of a double sodium line at D."* The triple line of magnesium coincident with b is so well seen in the spectrum of this star that I made use of these lines in my determination of the star's motion in the line of sight in 1871.

* *Phil. Trans.*, 1864, p. 428.

In the photographic spectrum a great many lines are seen in the part of the spectrum which is less refrangible than that included in my map, namely, from about λ to G. The whole photographic spectrum is crowded with lines similar in general characters to those of the solar spectrum. Twenty-one of the stronger of these lines have been measured and are given in the map. Several of these agree in position with similar lines in the solar spectrum.

On the more refrangible side of λ the appearance of a bright band is seen which suggests a bright line. After a careful examination of the two negatives which I have of this star, and of positives taken from them, I have come to the conclusion that this appearance is really due to the absence of the finer lines which probably crowd the other parts of the spectrum, though they are too fine and close to be seen separately in the photographs.

Beyond K we have a strong contrast presented in the character of the lines. Here the lines are much broader and more intense, and arranged more or less in triple and other forms of grouping with finer lines between.

The stronger lines only of the crowded spectrum have been measured and inserted in the map. There are lines corresponding to some of the lines of the Vega class.

The dissimilarity of this spectrum from the class of white stars is further seen in the circumstance that as far as the spectrum can be traced upon the plate it is crowded with lines, as is the case in the solar spectrum. The portion of the spectrum beyond H is unlike the solar spectrum in character, as will be at once apparent upon an inspection of the map.

LINES

W. L.		W. L.
H ₁ 4340	as in solar spectrum.	4055
4325	{ doubtless the group G	4045
4307.5	} clearly multiple.	4034
4289		4040
4271	stronger.	3995
4252.5		3980
4237.5		H ₁ 3968
4227.5		H ₂ 3933
4214		3920
4201		3905
4195		3900
4185	thin.	a 3887.5
4176		3881
4170		3870
4150	{ probable group.	3859
4141		3856
4132.5	thin rather.	3850
4112		3838
λ 4099		3835
4075		3832.5
4064		a 3822.5

LINES (*continued*)

	W. L.		W. L.
	3815		3657·5
	3814·5		3641
	3810		3637·5
	3805		3625
	3798		3610
γ	3795		3602·5
	3789		3592·5
	3775		3585
	3762·5		3575
	3755		3560
ε	3745·5		3551
	3732·5		3515
ζ	3730		3507·5
η	3717·5		3504·5
θ	3707·5		3487
	3702·5		3482
	3690		3475
	3682·5		3467
	3672·5		3457
	3662·5		

THE MAP

M. CORNU's map of this region of the spectrum is placed at the top and bottom of the map. The portion from G to H is on the same scale, and for this part ÅNGSTRÖM's map of the solar spectrum has been made use of. An attempt has been made to give, approximately, the relative intensity and character of the stellar lines. The lines have been carefully laid down, but for any purposes requiring great accuracy, use should be made of the tables of wave-lengths.

(For photographs of the Spectra of the Planets, see Section VIII., p. 380.)

ADDENDUM. Added March 10, 1880

Since this paper was sent to the Royal Society the following observations have been made:—

Sirius.—A photograph was taken January 2, 1880, which possesses better definition than those taken previously. In this photograph a fine line at the position of K is seen, of about the same intensity as the line in the spectrum of Vega. The typical lines are in a small degree broader and more diffused at the edges than is the case in the spectrum of Vega.

I cannot see with certainty more than ten of the typical lines. I am unable to say if the remaining lines θ and ι are really absent or very faint.

Rigel.—Photograph taken January 3, 1880. All the typical lines are seen. They are rather broader than in the spectrum of α Cygni, but not quite so broad as in α Virginis. In the arrangement I have adopted in the map, Rigel

should be placed between these two stars. There is a thin defined line at the position of K. I have a suspicion of lines beyond the typical group, and also of a line between α and β at $\lambda 3862\cdot 5$, and a line between β and γ .

Betelgeux.—Photographs were obtained of this star February 17, 1877, but in a photograph taken February 17, 1880, the spectrum is better defined. It is difficult to obtain a photograph of this star. An exposure forty times greater than would have been necessary for a good spectrum of Sirius gave but a faint spectrum of limited extent of Betelgeux. The photographic impression is strongest about G. On the less refrangible side it can be traced to F; on the other side it appears to end abruptly at H, but by careful illumination a faint trace of the spectrum can be traced to a short distance beyond H.

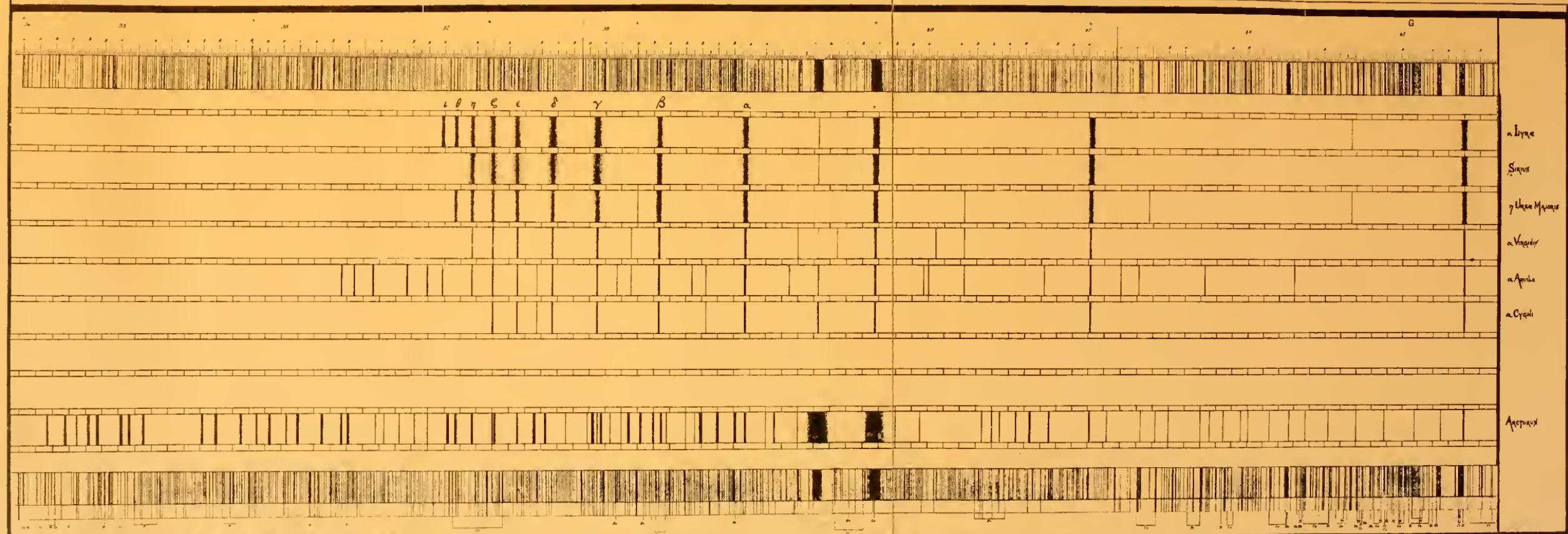
Of the visible spectrum of this star, Dr. Miller and myself remark (*Phil. Trans.*, 1864, p. 425, and Plate 9): "The light of this star has a decided orange tinge. None of the stars we have examined exhibits a more complex or remarkable spectrum. Strong groups of lines are visible in the red, the green, and blue portions." The measures are given of about eighty lines. At that time we were not able to see the lines of hydrogen at the positions C and F.

Later (*Proc. Roy. Soc.*, 1872, p. 388) I remark on this point: "I was able with the more powerful instruments at my command to see a narrow defined line in the red apparently coincident with $H\alpha$, and a similar line at the position of $H\beta$. The line $H\alpha$ falls on the less refrangible side of a small group of strong lines. $H\beta$ occurs in the space between two groups of strong lines, where the lines are faint."

In the photograph there is a line apparently coincident with $H\gamma$ (near G), but it is not strong. The spectrum about H is too faint for any certainty as to the characters of the lines H and K, which I believe are present. I give the wave-lengths of some of the most conspicuous lines between G and H.

4340		4145
4319		4132
4298·5		4099
4252		4075
4226		4025
4171		

Aldebaran.—The light of this star is of a pale red. We described the visible spectrum with some minuteness (*Phil. Trans.* 1864, p. 424, Plate 11). This star requires a very long exposure. An exposure fifty times greater than would have been necessary for Sirius gives a spectrum extending from about F to H, with a faint trace of the more refrangible portion. The part from F to H is strongly photographed and well defined. It is crowded with lines. About fifty of the stronger lines could be measured without much difficulty; but unfortunately, from clouds coming on, the spectrum of Capella, which was



taken on the same plate, is too weak to give with accuracy a fiducial point from which to take the measures. The less refrangible part of the photographed portion of the spectrum (roughly from F to G) is brighter (darker in the negative) from fewer lines of absorption. In the other portion (from about G to H) the lines are more numerous, and exhibit a different character, being broader, more intense, and probably more diffused at the edges.

Capella.—The spectrum of this star was photographed by Dr. Miller and myself in February, 1863. It is a white star, and exhibits a visible spectrum closely resembling that of our sun.

The photographs recently obtained exhibit a spectrum from F to beyond S, which so closely resembles the solar spectrum that a photograph of this star would, at first sight, be taken for a solar one. This close general resemblance is even maintained on closer scrutiny. The lines G, H, and K are of about the same intensity and breadth as in the solar spectrum. Beyond H several of the more distinctive groupings of the solar lines are clearly seen in the spectrum of this star. I have not attempted to measure the lines in detail, for the task would be as great as the measuring of the corresponding parts of the solar spectrum.

The great interest of this star in connection with the researches contained in this paper is that it appears to be a sun in the same stage as that in which our sun is.

Whether the order of change from the more simple typical spectrum in which these researches show that the stars may be arranged, also indicates some of the successive stages of their life changes through which they pass is a point on which we know nothing certainly. On this hypothesis the stars which have been observed would have to be arranged approximately in the following order * :—

Sirius.	Vega.
η Ursæ Majoris.	
α Virginis.	
α Aquilæ.	
Rigel.	
α Cygni.	
:	
:	
Capella.	The Sun.
Arcturus.	
Aldebaran.	
Betelgeux?	

* According to the reasoning of Mr. Johnstone Stoney, the changes of the stars in time would be in the inverse order of the arrangement I have suggested in the text. (See *Proc. Roy. Soc.*, vol. xvii., pp. 47-51.)

[For my later photographs of the spectra of the stars, see *Atlas of Representative Stellar Spectra*, Plates I.—XII. In the text will be found a full discussion of the order of stellar evolution.]

ON THE LIMIT OF SOLAR AND STELLAR LIGHT IN THE ULTRA-VIOLET PART OF THE SPECTRUM

(From *Proc. Roy. Soc.*, vol. xlvi., p. 134, 1889)

IT has been long known that the solar spectrum stops abruptly, but not quite suddenly, at the ultra-violet end, and much sooner than the spectra of many terrestrial sources of light. The observations of Cornu, of Hartley, and, quite recently, of Liveing and Dewar, appear to show that the definite absorption to which the very rapid extinction of the solar spectrum is due has its seat in the earth's atmosphere, and not in that of the sun; and that, consequently, all ex-terrestrial light should be cut off at the same place in the spectrum.

During several years I have attempted to obtain the limit in the ultra-violet for stellar light here, but as it was necessary to make use of a bright star at a high altitude, and at a time when the atmosphere was very clear, it was not until September 20, 1888, that I was able to obtain a result which seemed to me to be satisfactory.

On that night three successive photographs of Vega, with increasing exposures, were taken on the same plate. The first spectrum was exposed for 10 minutes, the second for 20 minutes, and the third spectrum nearly four times as long, namely, for 70 minutes.

A comparison of the extent of the second spectrum due to an exposure of 20 minutes with that of the third spectrum, to which an exposure of 70 minutes was given, leaves no doubt that the latter spectrum has reached the limit imposed by atmospheric absorption, and has not stopped in consequence of an insufficient exposure of the plate.

The original plate has been enlarged about four times; and a spectrum of magnesium and calcium, taken with the same apparatus, and enlarged simultaneously with the plate of stellar spectra, has been placed above to serve as a scale.

As the spectra are prismatic, it is not possible to indicate the wave-lengths in a scale of equal parts. A short scale only is placed over the spectrum where the light of Vega ends.

The spectroscope with which the spectra were taken is furnished with a prism of Iceland spar and lenses of rock crystal, and a mirror of speculum metal was used to condense the light of Vega upon the slit.

It will be seen that at my observatory* the light of Vega at about $\lambda 3000$ is abruptly weakened, and then continues as a very faint line to the point of apparent extinction at $\lambda 2970$.

* Elevation of the observatory 177 feet above mean sea-level. Barometer about 30.03 inches at the time of observation.

Numerous solar spectra taken here during the last four years with the same spectroscope show an average abrupt weakening at about $\lambda 3000$, and an apparent total extinction at about $\lambda 2985$.

On two occasions only the very faint weakened spectrum could be traced as far as $\lambda 2970$.

The abrupt narrowing of the spectrum at the end towards the red is produced by the rapid falling off of sensitiveness of the silver bromide for light of increasing wave-length.

The increase of breadth of the spectra with increase of duration of exposure is due to the same causes, optical and photographic, which produce the increase of diameter of stellar disks on the photographic plate with longer exposures, when a reflector is used. At h the breadths of the spectra, having 20 minutes' and 70 minutes' exposure respectively, are 0.06 inch and 0.105 inch.*

In 1879 Cornu † made experiments on the limit of the solar spectrum with reference to the altitude of the place of observation. On the Riffelberg, at an elevation of 8414 feet, the spectrum reached to $\lambda 2932$, while at the lower elevation of Viège, 2163 feet, the spectrum stopped at 2954. He concludes that the absorption is due to the gaseous constituents, and not to aqueous vapour in the atmosphere.

In 1881 ‡ Hartley stated that an amount of ozone proportional to the average quantity in a vertical column of the atmosphere caused an absorption similar to that observed in the solar spectrum—namely, terminating about $\lambda 2950$.

Quite recently Liveing and Dewar have made some important experiments on the absorption-spectrum of large masses of oxygen under pressure. § They state that with a tube 165 cm. long and a pressure of 85 atmos., oxygen appeared to be quite transparent for violet and ultra-violet rays up to about $\lambda 2745$. From that point the light gradually diminished, and beyond $\lambda 2664$ appeared to be wholly absorbed.

In some later experiments with a steel tube 18 metres long and a pressure of 90 atmos., oxygen produced complete absorption above P, i.e., $\lambda 3359.2$.

M. Janssen, from his observations on the Alps, concludes that both the bands which follow the law of the square of the density, and the dark lines

* The law of increase of size of image with exposure is not as yet accurately defined. Bond found that the diameter of star-disks varied nearly as the square root of the time of exposure. Pritchard, using a reflector, found a law near the fourth root; and Mr. H. H. Turner has recently found a law very near the cube root for plates taken with a photoheliograph object-glass (*Astron. Soc. Month. Not.*, vol. xlix., p. 292).

† "Sur l'Absorption atmosphérique des Radiations ultra-violettes," *Journ. de Physique*, vol. x., 1881.

‡ "On the Absorption Spectrum of Ozone, and on the Absorption of Solar Rays by Atmospheric Ozone," *Chem. Soc. Journ.*, vol. xxxix., 1881, pp. 57, 111-129.

§ *Chemical News*, vol. lviii., p. 163, and *Phil. Mag.*, September, 1888, pp. 286-290.

obeying a different law of formation, which are due to oxygen in the solar spectrum, are produced exclusively by the earth's atmosphere—"L'atmosphère solaire n'intervient pas dans le phénomène."*

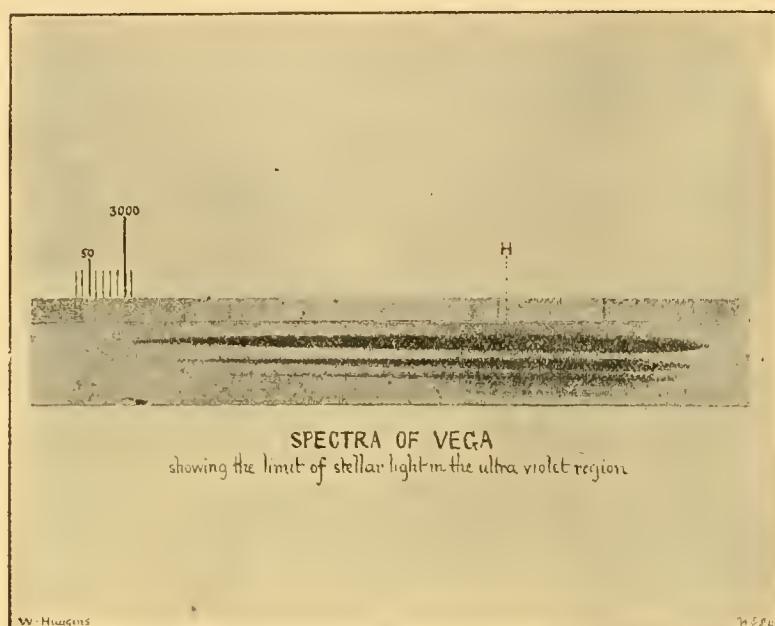


Fig. 15.

ON A NEW GROUP OF LINES IN THE PHOTOGRAPHIC SPECTRUM OF SIRIUS

(From *Proc. Roy. Soc.*, vol. xlvi., p. 216, 1890)

IN 1879 † I gave an account of a series of broad lines in the photographic region of the spectrum which was found to be characteristic of Sirius, Vega, and other white stars, and which was identified as a continuation of the spectrum of hydrogen beyond H.‡ In the photographs of Sirius which I had taken up to that time, I was not able to be certain if the two most refrangible of the lines, θ and ι , were present. This uncertainty has been set at rest by photographs taken since, in which the complete series of the hydrogen lines, including θ and ι , come out with great distinctness.

I have long suspected the presence of another group of broad lines some distance farther on in the ultra-violet region, but until this year we have not been able to see them in the photographs with sufficient distinctness to be able to make even roughly approximate measures of their positions.

* *Comptes rendus*, vol. cvii., p. 677.

† *Phil. Trans.*, 1880, p. 669.

‡ H. W. Vogel, *Berlin. Akad. Monatsber.*, 1879, July 10; and Cornu, *Journal de Physique*, 2nd ser., vol. v., 1886, p. 100.

On April 4 a photograph of the spectrum of Sirius was taken with a long exposure, the slit being made very narrow, in the hope of bringing out this new group of lines with greater distinctness. This plate shows, on examination, that the spectrum of Sirius, after the termination of the hydrogen series, remains, as far as we can see at present, free from any strong lines until a position as far in the ultra-violet as about λ 3338 is reached, at which place appears the first of a group of at least six lines, all nearly as broad as those of the hydrogen series. The third line of the group, about λ 3278, appears to be the broadest; but they are all broad, though even in this photograph they are not seen with the distinctness which is necessary for ascertaining accurately their relative character.

The sixth line occurs where the spectrum is faint, almost at the limit of this photograph, which was taken when Sirius was some distance past the meridian, and we are not able to find out whether this line completes the group, or whether there may not be other lines still more refrangible belonging to it. We expect to be able to determine this point, namely, whether the group ends with the sixth line, when the opportunity comes round of being able to photograph the star when it is near the meridian.

The new group of six lines is well seen when the photograph is examined with a lens, but when the plate is placed under the measuring microscope it is only with some difficulty that the lines can be observed with the distinctness which is necessary for measuring them with a fair approach to accuracy.

For this reason, the wave-lengths given below must be regarded as only preliminary, and but roughly approximate measures of the positions of the new lines :

1st Line	λ 3338		4th Line	λ 3254
2nd "	λ 3311		5th "	λ 3226
3rd "	λ 3278		6th "	λ 3199

ON WOLF AND RAYET'S BRIGHT-LINE STARS IN CYGNUS

(From *Proc. Roy. Soc.*, vol. xlix., p. 33, 1890)

IN 1867 MM. Wolf and Rayet discovered at the Paris Observatory three small stars in Cygnus, which in the spectroscope showed several bright lines upon a continuous spectrum.* All three stars have a very bright band in the blue part of the spectrum.

These stars are :

- B.D. +35°, No. 4001.
- B.D. +35°, No. 4013.
- B.D. +36°, No. 3956.

* *Comptes rendus*, vol. lxxv., 1867, p. 292.

Their spectra were described in 1873 by Vogel, whose observations agree substantially with the original description given by Wolf and Rayet.* A more complete account of their spectra was given by Vogel in 1883, from observations at Vienna with the 27-inch refractor made by Sir Howard Grubb.†

Vogel's measures of the bright blue band place it in the star No. 3956 at from $\lambda 468$ to $\lambda 461$, with a maximum at $\lambda 464$; in the star No. 4013 with a maximum at the place in the spectrum; while the corresponding blue band in the star No. 4001 has a considerably less refrangible position, commencing at $\lambda 470$, reaching a maximum at $\lambda 468$, and ending about $\lambda 465$.

These later measures, though they differ from his earlier ones, in so

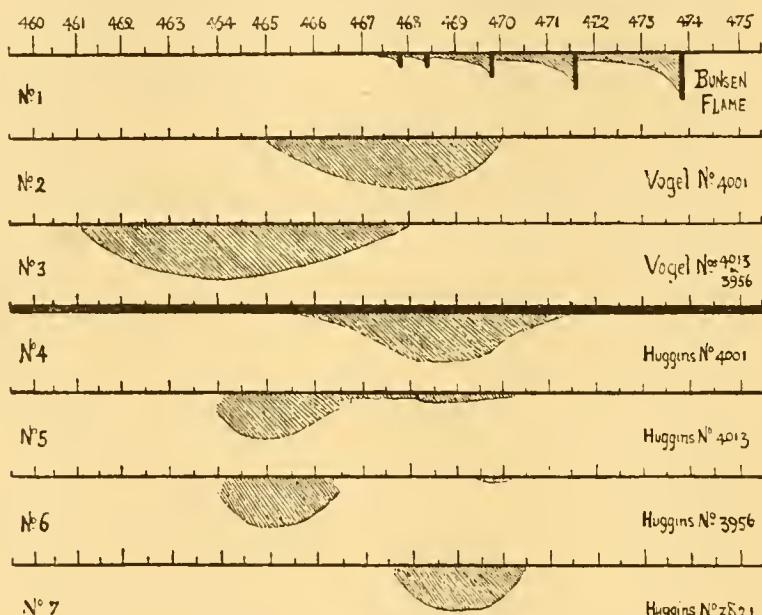


Fig. 16.

far as they show that the blue band has not an identical position in all three stars, nevertheless support substantially his earlier observations, which Vogel considered to show, contrary to the statements of Secchi, that the bright lines, including the blue band, were not due to carbon.

In the diagram, Nos. 1, 2 and 3 show the positions of the bright bands in the three stars, according to Vogel's measures, relatively to the blue band of the hydrocarbon flame.

Vogel's measures are :—

		Beginning of the band.	Brightest part.	End of the band.
Star No. 4001		$\lambda 470$	$\lambda 468$	$\lambda 465$
„ 4013		—	$\lambda 464$	—
„ 3956		$\lambda 468$	$\lambda 464$	$\lambda 461$

* Berichte K. Sachs. Ges. der Wiss., Dec. 1873, p. 556.

† "Publicationen Astrophys. Observ., Potsdam," vol. iv., No. 14, pp. 17-21.

His diagram shows the band in No. 4013 to begin and end at about the same positions as in the star 3956.

It has been stated recently that the bright blue band in all three stars is the carbon band in the blue, commencing near λ 474;* and more recently, notwithstanding the difference of position, according to Vogel, of the band in one of the stars from that which it occupies in the other two of as much as λ 0040, that direct comparisons showed an absolute coincidence of the band in all three stars with the blue band of a spirit-lamp flame.†

As the presence or absence of carbon in these stars, as shown by the coincidence or otherwise of the blue band with that of the hydrocarbon flame, was of great importance to us in connection with a wider investigation on which we are at work, we thought it necessary, after these recent statements as to the position of the band, to make direct comparisons of the spectra of these stars with that of the hydrocarbon flame under sufficiently large dispersion to enable us to determine whether Vogel's measures are substantially correct, or whether they are so largely in error as the absolute coincidence of the band with the blue band of a spirit-lamp flame in the case of all three stars would show them to be.

The obvious importance of making the observations with sufficient dispersion is supported by Vogel's own experience. With the small dispersion which he employed in his earlier observations in 1873, he did not detect the large

* Professor Lockyer, in the Bakerian Lecture for 1888 (*Proc. Roy. Soc.*, vol. lxiv., p. 37), says of the star No. 4001: "The bright band with its maximum at λ 468 is the bright carbon fluting commencing at λ 474 and extending towards the blue, with its maximum at 468, as photographed at Kensington."

Of the star 4013: "The bright band in the blue at 473 is most probably the carbon band bright upon a faint continuous spectrum, this producing the absorption from 486 to 473" (*loc. cit.*, p. 41).

Of the star No. 3956: "The bright band at 470 is the carbon band in the blue, commencing at 474, with its maximum at about 468, as observed and photographed at Kensington" (*loc. cit.*, p. 43). See Vogel's measures for the band in this star, which are given in the text.

Diagrams of the spectra of these stars are given at pp. 38, 40, and 41, based on Vogel's observations and his curves, which, on a slightly reduced scale, are placed at the bottom of the diagrams. The maximum of Vogel's curves is placed in all three diagrams at λ 468, and agrees in the diagrams with the carbon band, whereas Vogel's original curves and his measures place the maximum in the case of two of the stars at λ 464, beyond the carbon band.

† Professor Lockyer, in a signed article in *Nature* (August 7, 1890, vol. xlii., p. 344), writes:

"In the Bakerian Lecture for 1888 I gave a complete discussion of the spectra of bright-lined stars, as far as the observations went, and the conclusion arrived at was that they were nothing more than swarms of meteorites a little more condensed than those which we know as nebulae. The main argument in favour of this conclusion was the presence of the bright fluting of carbon which extends from 468 to 474. This standing out bright beyond their short continuous spectrum gives rise to an apparent absorption band in the blue. . . . Direct comparisons of the spectrum of all the three stars in Cygnus with the flame of a spirit-lamp have been made by Mr. Fowler, and these showed an absolute coincidence of the bright band in the stars with the blue band of carbon seen in the flame. It was found quite easy to get the narrow spectrum of the star superposed upon the broader spectrum of the flame so that both could be observed simultaneously."

difference of position, about λ 4040, of the band in No. 4001, as compared with its position in the other two stars. On this point Vogel says, in his memoir of 1883: "Etwas abweichend ist nur die Auffassung der Lage der breiten hellen Bande im Blau, die bei den früheren Messungen bei allen drei Sternen übereinstimmt. . . . Bei den verhältnissmässig geringen optischen Hülfsmitteln, mit denen jene Messungen ausgeführt wurden, ist die Uebereinstimmung aber eine ganz überraschende" (*loc. cit.*, p. 21).

We observed the spectra of the stars successively, first with a direct-vision prism of small dispersion, then with a spectroscope (A) containing one prism of 60° , and finally with a spectroscope (B) with two compound prisms, equal to about four prisms of 60° ; with the last-named instrument the comparisons with the hydrocarbon flame were made.

A rapid preliminary comparison in the spectroscope (B) of the spectra of the three stars with the blue base of a Bunsen flame showed at once the substantial accuracy of Vogel's measures, and the striking difference of position of the band in the star No. 4001 from that which it holds in the other two stars.

The obvious want of agreement of the star bands with the blue band of the Bunsen flame was seen at once. Their relative positions appeared to agree substantially with the positions represented in No. 2 and No. 3 of the diagram, which are based on Vogel's measures. More careful and repeated observations brought out clearly, as is indeed shown by Vogel's curve, that the star bands differ in character as well as in position from the blue band of the hydrocarbon flame, and also in some respects from each other.

Before giving in more detail the results of our observation on each of the three stars, it should be stated that in all the stars the continuous spectrum is not in our instruments a short one, ending before the position of the bright blue band is reached. On the contrary, an examination with all three spectroscopes showed that the continuous spectrum, though enfeebled by absorption a little before reaching the blue band, can be traced, as is shown in Vogel's curves, quite up to the band, and indeed extends for a long distance into the violet beyond the blue band. The blue band does not in our instruments stand out bright beyond the end of a short continuous spectrum, but falls upon a fairly luminous continuous spectrum, which can be traced past the blue band into the violet, apparently as far as the eye could be expected to follow it.

We suspected bright lines or bands in the region more refrangible than the blue band, but in such faint objects this is a point which should be determined by photography.

Professor E. C. Pickering has since kindly informed us that his photographs of the star No. 4001, which extend into the ultra-violet region, show

beyond the blue band the bright hydrogen lines at 434, 410, 397, and 389; and also other bright lines at 462, 455, 420, 406, 402, 395, and 388.

In his photographs of the stars 4013 and 3956, however, the only well-marked line is in the blue at 470.

Star 4001.—In this star, as is shown by Vogel's measures and curve, the bright blue band is less refrangible than in the other two stars, and approaches therefore nearer to the position of the blue band of the hydrocarbon flame. The appearance and position of the band in the star as contrasted with that of carbon, when observed in spectroscope B, are represented in spectrum No. 4 of the diagram.

The brightest part of the band, from about λ 468 to λ 469, falls off rather suddenly in brightness at about these wave-lengths, but can be traced towards the red as far as about λ 471.5, and as far in the blue as about λ 465.5.

In our observations of this and the other stars we did not attempt micrometric measures of the blue band, but we estimated their positions by means of the intervals between the five flutings of the band of the Bunsen flame. In the case of objects so faint in our instrument when viewed under the dispersion of spectroscope B, we did not consider there would be any real gain of accuracy by attempting to take measures.

Though the wave-lengths assigned to our positions must therefore be regarded as not more than approximately correct, we have no hesitation in considering them fully accurate enough for the purpose of our investigation.

The star band is not split up into well-separated maxima, as is the Bunsen flame band, but we have little doubt that the brightest part of the band, from λ 468 to λ 469, which is much, and rather suddenly, brighter than its beginning and termination, consists of bright lines. Lines appear to flash out at moments, but in our instruments they cannot be seen with sufficient steadiness for us to be sure of their number and position.

Under certain conditions of the electric discharge, the normal relative brightness of the component flutings of the blue hydrocarbon band has been observed to be so far changed that the position of maximum intensity is moved from the less refrangible end of the band towards the blue end; but the five flutings remain without any change of their position in the spectrum.*

Dr. Hasselberg, by means of feeble disruptive discharges from tinfoil

* "It is necessary to state that the maximum luminosity of the blue band, under some conditions, is about 468. . . . The conditions under which this band has its maximum luminosity at 468 in Geissler tubes seem to be those of maximum conductivity. If the pressure be high, all the members of the group are sharp, and the luminosity of the band is almost uniform throughout. This always occurs when the pressure is very low. At intermediate stages of pressure, however, the luminosity has a very decided maximum at about 468" (Appendix to the Bakerian Lecture for 1888, *Proc. Roy. Soc.*, vol. xlv., pp. 167, 168).

terminals placed outside an exhausted tube containing vapour of benzole, obtained a nearly pure spectrum of the order of that in a hydrocarbon flame mixed only with faint lines of hydrogen. He says: "Es war aber hier die violette Gruppe sehr schwach. Dagegen schien mir die blaue Gruppe relativ heller als im Flammenspectrum, und sie hatte ausserdem entschieden ihre grösste Intensität nicht an der weniger brechbaren Kante, sondern mehr nach dem Violetten hin. Dasselbe schien mir auch mit der gelben Gruppe der Fall zu sein. In Bezug auf die grüne Gruppe konnte ich aber keine Verschiebung des Intensitätsmaximums bemerken."

Dr. Hasselberg gives curves to show the amount of this change of intensity in the blue group and in the orange group. In the blue group the maximum is moved from the first to the third line, that is, to about λ 4698. His curve gives the brightness of the maximum over that of the first line as about 7 to 6, whereas the normal relative intensity of these two lines is in the inverse direction and as about 2 to 4 (Watts, "Index of Spectra," p. 30).*

A similar change from the normal relation of brightness of the flutings within the band, even if removed to λ 468, does not seem to us to bring the star band sufficiently into accordance in character and position with those of the band of the hydrocarbon flame to justify us in attributing the blue band in the star to carbon. Though we traced the band a little farther towards the red than the position of the beginning of the band given by Vogel's measures, yet it is very faint, and without any increase in brightness at the place of the second fluting of the carbon band, beyond which we were unable to see it.

According to Hasselberg's curve, the second bright fluting, where in our instruments the star band ends, still retains a brightness of about $\frac{1}{2}$ of that of the maximum, and the first line, at the position of which no brightening of the feeble continuous spectrum of the star could be detected, a brightness of about $\frac{6}{7}$ of that of the maximum. That the flutings of the band were not obscured by the absorption band at this part of the spectrum appears clear from the circumstance that we could trace the faint continuous spectrum up to the bright band.

Vogel's and our observations agree in making the band run on some distance beyond the visible termination of the blue band of the Bunsen flame. Piazzi Smyth, under some conditions, observed a large number of faint "linelets" beyond the "5th leader" of the band, where its visibility usually ends; and in the brilliant light of the arc the band can be traced farther in the blue. The extension of the band under such circumstances does not seem to us to affect our present argument; for in the very feeble light of the star we may surely take it that the carbon band, if present, could not be seen to

* *Mém. de l'Acad. Imp. des Sciences de St. Pétersbourg*, vol. xxii., No. 2, 1880, p. 82.

extend farther than its usual visible limit in a Bunsen flame—namely, about $\lambda 468$.

Perhaps it should be stated, in connection with the circumstance that we saw the band extend a little farther towards the red than Vogel did, that at the time of our observations the hydrogen line at F was not visible in our instruments, whereas it was bright at the time when Vogel observed the star. In the spectrum of a similar star, D.M. + 37° 3821, in which the hydrogen line at F at the time was bright, the blue band was seen by us to stop near the place given by Vogel in his measures of the star No. 4001.

Not only is there no coincidence, so far as Vogel and we have observed, of the position of the band in the star with that of the blue band of the Bunsen flame; but, further, the want of accordance of its general characters is so great as to make the view that its origin is carbon very improbable. This improbability is very greatly increased when we find, as will be shown presently, that no traces whatever of the very bright beginnings of the more brilliant green and orange bands could be detected by us in any of the stars. Further, Professor E. C. Pickering has kindly sent to us an account of his photographs of this star, which, though they show the hydrogen line at $\lambda 434$, do not exhibit any brightness at the positions of the indigo hydrocarbon bands, beginning near 4312, and $\lambda 4382$.

This star, however, can scarcely be taken by itself; in the case of the other two stars, in the spectra of which, according to Vogel's, Copeland's, and our own observations, the brightest part of the blue band is from $\lambda 464$ to $\lambda 465$, but nearer $\lambda 465$, quite outside the ordinary visible limit of the carbon band, the evidence seems very strong indeed that the band does not owe its origin to carbon.

We satisfied ourselves that when the spectrum of the star is examined under the dispersion of spectroscope B, none of the brighter parts of its spectrum fell at, or very near, the green, orange, and indigo flatings of the hydrocarbon flame spectrum; at these positions we were unable to detect any sensible brightening of the star's spectrum. Professor Copeland's measure of the blue band in 1884 was $\lambda 469.5$.

No. 4013.—Vogel does not give measures of the beginning and the ending of the band in this star, but only of the brightest part: “Hellste Stelle, nahezu Mitte, einer breiten verwaschenen Bande, $\lambda 464$.” He gives, however, a diagram of the spectrum in which the bright blue band is represented as substantially coincident in position and in general character with that in the spectrum of No. 3956.

Our observations agree substantially with those of Vogel, but they make the band to consist of two parts—a very bright part, from about $\lambda 466$ to $\lambda 464$, but brightest near $\lambda 465$, and a very faint band, apparently detached

from the bright one from about $\lambda 4685$ to about $\lambda 4705$. This faint band is brightest near where it ends rather abruptly at the more refrangible end. The very bright band has not the character of a fluting, nor is it broken up into maxima widely separated like those of the Bunsen flame band, but appears to be a group of bright lines. The lines were only glimpsed at moments; it is therefore difficult to make a drawing which truly represents the character of the band as seen in our instruments. The band, which is shown at No. 5 of the diagram, is left unfinished at the more refrangible end, as we were not certain how far we ought to consider it to extend.

In this star (as we shall show to be the case in No. 3956 also) the great body of bright radiation lies far beyond the ordinary visible limit of the blue carbon band, and no connection whatever with carbon is even suggested to us by the star's spectrum. Dr. Copeland's measure of the band in 1884 was $\lambda 465\cdot4$.

The continuous spectrum of the star is unequally bright from the presence of bright groups and also apparently of absorption bands or lines, and therefore with small dispersion it might be easily supposed that the spectrum is brighter at the position of the green carbon band. We examined the continuous spectrum repeatedly with great care, and we were able to satisfy ourselves that, under the considerable dispersion of our instruments, there was no sensible brightening of the spectrum at the positions of the green and of the orange bands of the Bunsen flame.

No. 3956.—Vogel places the brightest part of the band in this star at the same position in the spectrum as in the star last considered, No. 4013—namely, at $\lambda 464$, a position beyond the carbon band. The position of the band as it appeared in spectroscope B, with the third eyepiece, is represented at No. 6 in the diagram. The position of the band relatively to that of the Bunsen flame was determined by estimations made by means of the intervals between the bright flutings of the Bunsen band. The position agrees substantially with that given by Vogel, but places the maximum brightness nearer to 465. This bright part probably consists of a group of bright lines, and falls off rather suddenly at both ends. We were not certain if the light beyond this bright part was due to a continuation of the band or to the continuous spectrum, more or less dimmed by absorption; we have, therefore, left the ends of the band incompletely in the diagram. Copeland's measure of this band in 1884 was $\lambda 464\cdot9$.

The sub-band seen in the star No. 4013 is very much fainter in this star, but we have little doubt that there is a very faint band present at about the same place in the spectrum.

Professor E. C. Pickering has found in the near neighbourhood of these

three stars other stars possessing bright lines in their spectra.* The brightest of these, independently discovered by Dr. Copeland in 1884,† namely, D.M. + 37° 3821, in which the spectrum is similar to that of the Wolf-Rayet stars, was examined. Dr. Copeland says of this star : "It has a spectrum of several bright lines near D, and a very bright band in wave-length 464" (*loc. cit.*). We were therefore surprised to find the blue band, which is very brilliant, not in the position of the band in the stars No. 4013 and No. 3956, but less refrangible, corresponding to the position of the band in the star No. 4001.

The bright band begins about λ 467 and runs on to nearly λ 470·5. It is clearly not made up of flutings similar to those of the Bunsen flame, but is a group of lines nearly uniformly bright throughout the length of the band. The band did not appear to extend in our instruments towards the red quite so far as the band of No. 4001; it stops near the place assigned by Vogel to the beginning of the band of No. 4001.

The band is represented in spectrum No. 7 in the diagram. Direct comparison with hydrogen showed that the line at F is brilliant in this star.

After some scrutiny of this part of the star's spectrum, we became conscious of a very feeble brightening of the spectrum beyond the bright band towards the violet, and as far as we could estimate its position, at about from λ 464 to λ 467, that is to say, about the position assigned to the band by Dr. Copeland in 1884.

We then re-examined the spectrum of No. 4001, and were able to feel pretty sure that a similar faint brightening of the spectrum occurs in this star also at the same place—namely, about the more refrangible position of the blue band in the stars No. 4013 and No. 3956.

Dr. Copeland, during his travels in the Andes in 1883, observed γ Argūs, and five small stars with bright lines in their spectra. He says: "As far as my measures and estimates go, all of them belong to the same class as the three Wolf-Rayet stars in the Swan, to which Professor Pickering has since added a fourth outlying member."‡

Dr. Copeland gives the position of the bright blue band in γ Argūs as λ 464·6.

Among the stars in the great cluster G.C. 4245, near ζ Scorpii, Dr. Copeland found a star, P. XVI 204 = Stone 9168, which has a similar spectrum,

* "The following list contains the designations of all eight stars (with bright lines), the first four being those previously known:—35° 4001, 35° 4013, 36° 3956, 36° 3987, 37° 3821, 38° 4010, 37° 3871, 35° 3952 or 3953. Of these 37° 3871 is P Cygni, and 37° 3821 is the star in the spectrum of which the bright lines are most distinct" (*letter in Nature*, vol. xxxiv., p. 440).

† *Monthly Notices R.A.S.*, vol. xlvi., p. 91, 1884.

‡ "An Account of some recent Astronomical Experiments at High Elevations in the Andes," "Copernicus," vol. iii., 1883.

namely, with a bright band in the blue and two in the yellow. He found the position of the blue band to be $\lambda 465\cdot 1$.

In the case of two other small stars with similar spectra, he found respectively for the blue band the approximate measures $\lambda 463\cdot 3$ and $\lambda 463\cdot 6$.

These four stars were similar, therefore, at the time of the observations, to No. 4013 and No. 3956, in which the maximum of the blue band is not far from $\lambda 464$, and therefore outside and beyond the ordinary visible limit of the blue carbon band.

Professor Vogel observed two other stars with similar spectra, of which the main feature is the very bright band in the blue region, namely, Arg. Oeltzen 17681 and Lal. 13412. These stars are too low in southern declination to be reached from our observatory.

Vogel places the blue band in Lal. 13412 at $\lambda 469$, which shows that it has a position similar to that of No. 4001 and of Dr. Copeland's star. In the case of Arg. Oeltzen 17681, Vogel makes the band to extend through about the entire range of refrangibility occupied by the two positions of the blue band in the Wolf-Rayet stars according to his measures of them—namely, from $\lambda 461$ to $\lambda 470$, with a maximum at the place where they would overlap, namely, $\lambda 466$.

Let us consider the four stars with an intensely brilliant blue band which we have examined: in two of them the band extends from about $\lambda 464$ to $\lambda 467$, and in the other pair the band has a less refrangible position, from about $\lambda 466$ to $\lambda 471$; but there is also in the case of each pair a very faint band visible, or suspected, at the position of the blue band in the other pair. Further, in Arg. Oeltzen 17681, Vogel found the bright band sufficiently long to include both positions of the band.

One suggestion which presents itself is whether these bands, or, more correctly, these groups of bright lines, may be variable, so that, under certain conditions, one or other of them becomes brilliant. Such a state of things would reconcile our observations of $+37^{\circ} 3821$ with the earlier measures of Dr. Copeland, and, indeed, might possibly explain, if this variability should be established, the circumstance that so accurate an observer as Professor Vogel did not detect, even with his smaller instrument in 1873, the very large difference of position of the band in 4001 from that of the corresponding band in the stars 4013 and 3956, which was so conspicuous in 1883, and is so still at the present time. In the broad characters of their spectra, and in their magnitudes, the Wolf-Rayet stars have remained unchanged since the discovery of their remarkable spectra in 1867.

As the only direct evidence of such a variability rests upon the change of position of the band in Dr. Copeland's star since his observation of it in 1884,

I wrote to Dr. Copeland to ask if his position rested upon sufficiently accurate measures or was arrived at by estimation only. In reply he says: "The place of the blue line (rather band) in D.M. $+37^{\circ} 3821$, given in the *Monthly Notices*, is a mere estimate to show the character of the star."

Whether any change of position of the band has taken place must therefore remain at present uncertain; but, independently of any such direct evidence of variability, the two positions of the very bright blue band, with the suspicion of faint bands at the alternate positions, appear to us suggestive of possible variation, especially when we consider that the spectra of these stars consist of numerous absorption bands and groups of bright lines upon a feeble continuous spectrum, a character of spectrum which seems to point to a probably unstable condition of the atmospheres of these stars.

The large difference of position of the bands in the two groups of stars is much too great to admit of an explanation founded upon a possible orbital motion of the stars. Besides, the near coincidence of Dr. Copeland's measures of two bright lines common to the stars 4001 and 4013 shows that the difference of position of the blue band is not due to motion in the line of sight.*

If future observations should show that the bright blue groups are variable, we must look, it would seem, to causes of a physical or a chemical nature.

If the two bright groups, differing in position by about $\lambda 0040$, belong to different substances, or, less probably, perhaps, to different molecular conditions of the same substance, it is conceivable that one or other substance, or molecular state, may predominate and appear brilliant, according to certain unknown conditions which may prevail in the stars' atmospheres.

It might be suggested that both bands are due to a long group of bright lines, extending from about $\lambda 461$ to $\lambda 471$, and that this long group is cut down by absorption bands; in one pair of stars an absorption from the green cuts off the less refrangible part of the long group down to about $\lambda 467$, while in the other two stars the more refrangible part is eclipsed, and the bright group appears as in 4001.

The appearance of the spectra in our instruments scarcely seems to us to be in accordance with such a view, because, though we did suspect brightenings in the alternate places, the appearance of the spectrum was not such as to suggest a bright group dimmed by absorption, for in that case the amount

* Dr. Copeland permits me to give the following measures of the bright lines in the Wolf-Rayet stars, which were made by him and Mr. Lohse on January 28, 1884:

Star.		1st yellow line.	2nd yellow line.	Bright line.	Faint line.	Large blue band.
$+35^{\circ}$ 4001	.	.	.	—	541·2(3)	522·0(1)
$+35^{\circ}$ 4013	.	:	:	582·4(2)	568·9(2)	541·0(2)
$+36^{\circ}$ 3956	.	.	.	581·0(2)	570·4(2)	—

of absorption needed to all but obliterate a group, as bright as it appears in the other pair of stars, would have blotted out completely the relatively feeble continuous spectrum. This continuous spectrum, though faint, was still distinctly seen.

More observations are needed, but it appeared to us desirable by these suggestions to invite the attention of observers to the points in question.

As the main object of our examination of these stars was to determine whether the bright band in the blue was to be regarded as showing the presence of carbon by its coincidence with the blue band of the hydrocarbon flame, we were not able, from the pressing claims of other work, to extend our examination to many other points in connection with the spectrum of these faint stars, for an exhaustive examination of which, indeed, our instruments are not sufficiently powerful.

We have stated already that the fairly luminous continuous spectrum reaches up to the bright band in all three stars, and extends beyond into the violet, as far as the eye could be expected to follow it.

The spectra are weakened at many points by what appear to be absorption bands, and are crossed by several brilliant lines, the positions of some of which have been given by Vogel and by Copeland.

An examination with spectroscope B of some of these bright lines, as they appear under small dispersion, showed them to be really not single lines, but short groups of closely adjacent bright lines.

One of the brightest of these lines is found in the star No. 4013, at the position, according to Vogel, of λ 570.

Dr. Copeland's measure for this line is λ 568·9 in star 4013, and λ 570·4 in the star 3956.

As this position is not very far from that of the green pair of sodium lines at λ 5687 and λ 5681, it has been suggested that the line in the stars is due to sodium, though there is no line of comparable brightness in the star's spectrum at the position of the dominant pair of the sodium spectrum at D.*

On confronting in spectroscope B the star line with the green sodium lines, the bright space in the star's spectrum was seen to consist of a short group of several bright lines close together, and nearly equally bright. This group appeared to extend through about four times the interval of the sodium pair, which would make the length of the group about λ 0024. The green sodium lines cross the group at about one-fourth to one-third of the length

* The 570 line is most probably the green sodium line 569, the absence of the yellow sodium being explained by the half-and-half absorption and radiation mentioned in the discussion of the causes which mask and prevent the appearance of a line in a spectrum (Bakerian Lecture for 1888 *Proc. Roy. Soc.*, vol. xliv., p. 41).

of the group from its more refrangible end. The group in the star is rather less bright at the two ends, but there is no gradual shading off in either direction, as in the case of a fluting.

When we examined this part of the spectrum with the small dispersion of a prism of 45° , we were pretty sure of a feeble bright line, less refrangible than the pair of bright groups in the yellow, and not far from the position of D. We were not able to see this line in spectroscope B with sufficient clearness to enable us to fix its position. It may be D, or perhaps more probably D₃.

In No. 4001, Vogel saw a line at the position of the F line of hydrogen. It is probable that this line, as is the case in so many stars in which it appears bright, is variable, as we were not able to see it when the H β line from a vacuum-tube was thrown in. In the similar star D.M. $+37^\circ 3821$, as we have stated already, the F line of hydrogen was very bright.

We were unable to detect in any of the stars a brightening of the spectrum at the position of the chief line of the bright-line nebulae. For this examination the lead line at $\lambda 5004\cdot5$ was thrown in, and the continuous spectrum of the star near to this position carefully scrutinised.

In their original paper, Wolf and Rayet state that they were not able to detect any nebulosity about the stars. They say: "Elles ne présentent non plus aucune trace de nébulosité" (*loc. cit.*, p. 292).

In a recent paper, Mr. Keeler, of the Lick Observatory, confirms this view. He says: "At my request, Mr. Burnham and Mr. Barnard examined the Wolf-Rayet stars in Cygnus for traces of surrounding nebulosity, but with only negative result."*

Notwithstanding these negative results, it appeared to us of great interest to ascertain further if any nebulosity would come out in a photograph of the stars taken with a long exposure.

Mr. Roberts responded at once to our wish when we asked his invaluable assistance, and on November 1st of this year he took a photograph of this region of Cygnus, with an exposure of two hours.

The three stars come out strongly upon the plate, but there is no nebulosity to be seen near any of them. There are faint stars in close proximity to the three stars, and apparently surrounding them, and, in the case of No. 3956, six of these faint stars are seen close to it, in an apparent spiral arrangement.

Though this surrounding of faint stars should be pointed out, it should at the same time be stated that the whole neighbouring region is so densely studded with similar faint stars that it would be rash, perhaps, at present to

* Publications of the Astronom. Soc. of the Pacific, No. 11.

suggest that this apparent connection of the bright-line stars with faint ones near them may be other than accidental.*

Professor E. C. Pickering informs me "that photographs have been obtained at the Harvard College Observatory of all the stars hitherto discovered whose spectra consist mainly of bright lines and are of the class discovered by Rayet. Part of these have been photographed at Cambridge, and the remainder in Peru." He states that they may be divided into three sub-classes, according to the characters of their fifteen bright lines. He says, further : "Photographs of the spectrum of planetary nebulae have also been obtained. They resemble closely the spectra described above, except that the line 500 is strongly marked ; 470 is seen in most of them, while the lines due to hydrogen are also bright."

It would seem that Professor Pickering's photographs do not permit him to distinguish the different positions of the bright blue band in some of these stars, for he gives for all the stars the same position, namely, λ 470.

We regret that the insufficiency of our instrumental means has left our examination of the spectra of these stars less complete than we could wish. Our observations appear to us, however, to be conclusive on the main object of our inquiry—namely, that the bright blue band in the three Wolf-Rayet stars in Cygnus, and in D.M. $+37^{\circ} 3821$, is not coincident with the blue band of the Bunsen flame.

OXYGEN IN HELIUM STARS

(From *Ast. Nach.*, Bd. 149, S. 231, 1899)

IN putting together for early publication photographs of star spectra taken here, I have found a confirmation of Mr. McClean's statement as to the presence of lines of oxygen in stars characterised by strong helium lines.

In the region of the spectrum beyond K, about ten lines given by Neovius as belonging to oxygen appear to coincide with lines in the spectra of Rigel,

* [Mr. Roberts has furnished us with the following description of the stars as they appear on his photograph :—

"No. 4001 appears as a multiple star made up of one bright, two fainter, and one very faint star partly behind the others; there is also a fourth bright star close to the multiple star. The group is surrounded by at least eight faint stars within a radial distance of $\pm 86''$ of arc from centre to centre.

"No. 4013.—The photo-image of this star is made up of three stellar images touching each other in a line slightly curved. Two are bright and one faint; and there are indications of two other faint stars behind the two bright ones. This multiple image of four or five stars is surrounded by five bright and seven faint stars; all within a radial distance of $82''$ of arc measured from centre to centre of the multiple star. The multiple image measures $\pm 55''$ in length and $\pm 19''$ in breadth.

"No. 3956.—Its photo-image is $\pm 27''$ in diameter. It is encircled by three stars of lesser brightness, and six faint ones within a radial distance of $59''$, i.e. there are nine stars within a radial distance of $59''$.—Dec. 5.]

of Lyrae, and of some other stars. The relative intensities of the stellar lines do not, in all cases, agree with those given to the lines of oxygen by Neovius.

These observations appear to me of sufficient interest to justify this preliminary note in anticipation of a fuller account which will appear in the book itself.

NITROGEN IN SOME HELIUM STARS

(From *Ast. Nach.*, Bd. 150, S. 109, 1899)

I WISH to add to my note,* on the presence of oxygen in stars characterised by strong helium lines, that in the spectra of some of these stars there is a dark line at the position of the strongest line of nitrogen at λ 3995. In Bellatrix there are also lines corresponding with other strong lines of nitrogen.

There seems to me a high probability that nitrogen is really present as well as oxygen.

LATER WORK ON THE SPECTRA OF THE STARS

AN account of our more recent work on the spectra of the stars, especially of the ultra-violet part of the spectrum, extending to λ 3300, has been given fully in Vol. I., *An Atlas of Representative Stellar Spectra*.

In that volume there is not only a detailed description of the separate spectra, but also a discussion of many problems suggested by the observations, among others: on the probable order of stellar evolution; on the temperatures of the different classes of stars; on the spectra of double stars with components of strongly contrasted colours, as indications of their relative ages; also on the photographs of the spectra of nebulae taken at an earlier date.

One of the points brought into prominence by the discussions in the *Atlas* is the general absorption existing in the atmospheres of the stars, and consequently the caution which is necessary in any attempt to determine the relative temperatures of the stars from the apparent relative intensities of the red and the blue radiations on the photographic plates, as if the stars were heated black bodies.

In the case of hot black bodies the absolute intensity of the red radiations rises with the temperature, though at a lower rate than that of the radiations in the blue and violet parts of the spectrum. Greater brightness, therefore, of the red end of a star, considered by itself alone, would indicate a higher temperature.

* *Ast. Nach.*, Bd. 149, S. 231, 1899.

The necessity for caution comes in when on the photograph it is found that the more refrangible parts of the star's spectrum are not as much relatively brighter as would be the case if we were photographing a heated black surface. In the case of a black body we should have to conclude against a higher temperature, and interpret the great brightness of the red as due to a larger surface at the lower temperature. In dealing with a star such a conclusion may be very far removed from the true interpretation.

There are three independent causes which may, severally or together, bring in a diminution of the brightness of the blue and violet parts of the spectrum of a star relatively to the red end :—

- (a) The selective absorption of the chemical substances of the star's atmosphere, which, as a rule, are more numerous and stronger in the more refrangible regions of the spectrum, and which vary enormously in their weakening effect upon the different parts of the spectrum in different classes of stars. (See *Atlas*, p. 80.)
- (b) A general absorption, and a scattering, in the star's atmosphere acting more strongly on the radiations of shorter wave-lengths.
- (c) A possible diminution of light in space acting most strongly on the smaller wave-lengths of the star's spectrum. This diminution may be due to an absorption, to a scattering from fine particles, or to both.

In the case of the solar star—the sun—Langley and Vogel have shown a strong general absorption, which acts more strongly upon the shorter wave-lengths. According to Vogel, the absorption of the smoke-like envelope of the sun, near the circumference, permits only about 13 per cent. of the violet rays to escape, increasing through the green and yellow to about 30 per cent. for the red. That, if this atmosphere were removed, the sun would be blue, since the intensity of the violet rays would be about three times as great as at present, while the red rays would be only one half again as bright. Schuster finds theoretically that "when the scattering (in a star's atmosphere) is molecular, it is sixteen times as large for the extreme visible violet as for the extreme visible red. Consequently the radiation emitted by a mass of gas under these conditions would show the violet considerably weakened as compared with the red. This opens out the possibility that with increasing temperature the violet portion of the spectrum of a star may diminish in intensity as compared with the red end . . . we possess some independent evidence that the photosphere emits less violet light than it should do if it were a black surface. . . . This consideration strengthens to some extent the idea that the comparative weakness of the ultra-violet radiation in solar stars is not due to a diminution of temperature" (*Astrophys. Journ.*, vol. xxi., pp. 20, 21).

And Pannekock says: "Il n'est pas impossible qu'une étoile à coloration plus rouge ait un pouvoir lumineux plus grand, si une température plus élevée.

et, en même temps, une plus forte absorption atmosphérique" (*Arch. Néerl.*, t. xii., p. 127).

In the *Atlas of Representative Stellar Spectra*, p. 156, *Plates XI. and XII.*, the spectra of the components of double stars showing contrasted colours, are discussed from the point of view of their probable relative evolutional stages. Assuming these double stars to have originated from one original mass, the components at their birth would have been in the same evolutionary stage, and composed mainly of the same substances. Their spectra should, then, indicate the stages of development they had severally reached, and it may be assumed that the successive stages would come in at an earlier time in the case of the component which has the smaller mass.

It is, however, the brighter star which shows the more advanced phase of development, while the relatively faint companion remains still in the earlier white-star stage.

We suggested, therefore, that the visually smaller star, usually bluish in colour, though so much less brilliant, might have the greater mass, and for this reason be still at an earlier evolutionary stage.

That some of the blue components have been found since to be spectroscopic close binaries does not seriously affect the argument, since from their close proximity and from their mutual radiation, the pair would not behave very differently, in the succession of their evolutionary phases, from a single body of corresponding mass.

Recently this view has received remarkable support from the work, on wholly independent lines, of Mr. T. Lewis on the relative masses of the components of eighteen binary stars. ("Measures of Double Stars," *Mem. Roy. Astron. Soc.*, vol. 56, p. xxi, 1906.)

Mr. Lewis' results are summed up as follows: "They [the relative masses] establish the curious persistency of an opposite disparity among the members of unequal pairs, between light and mass. The apparent satellite is in fact the primary of the system." (See also *Astrophys. Journ.*, vol. xxv., p. 65, 1907.)

On this view the strongly contrasted spectra of these double stars bear strong witness against the theory that the different classes of star-spectra are due to original differences of the cosmical substances, or of their relative proportions, existing in various parts of the heavens; whether these substances are regarded as the stuff out of which the stars were formed, or as existing possibly in the parts of space surrounding the stars, and so bombarding them from without.

On the contrary, the spectra of these double stars—as, for example, the late white-star spectrum of the blue star of γ Andromedæ and the post-solar spectrum of the orange companion—are in favour of the view taken in my

Papers and supported in the *Atlas* (p. 74), that these class-differences indicate the successive stages of a stellar evolution. Undoubtedly the component bodies of these double stars would consist mainly of the same substances, however they were formed; while the parts of space in which they severally exist are closely adjacent—or rather really continuous—and so any matter possibly existing therein cannot differ greatly, if at all, in its chemical nature. [1909.]

Section III
SPECTRA OF NEBULÆ

LIST OF PAPERS

"On the Spectra of some of the Nebulæ."

Phil. Trans., vol. cliv., pp. 437-444. *Phil. Mag.*, vol. xxxi., p. 523.
1864. P. 108.

"On the Spectrum of the Great Nebula in Orion."

Proc. Roy. Soc., vol. xiv., p. 39. Also *Month. Not.*, vol. xxv.,
p. 155. 1865. P. 116.

"Further Observations on the Spectra of some of the Nebulæ, with a
Mode of Determining the Brightness of these Bodies."

Phil. Trans., vol. clvi., p. 381. *Phil. Mag.*, vol. xxxi., p. 475. 1866.
P. 120.

"Further Observations of the Spectra of the Nebulæ."

Phil. Trans., vol. clviii., p. 540. 1868. P. 137.

"On the Spectrum of the Great Nebula in Orion; and on the Motions of
Stars towards and from the Earth."

Proc. Roy. Soc., vol. xx., p. 379. 1872. P. 144.

"On the Inferences to be Drawn from the Appearance of Bright Lines
in the Spectra of the Irresolvable Nebulæ."

Proc. Roy. Soc., vol. xxvi., p. 179. 1877. P. 150.

"On the Photographic Spectrum of the Great Nebula in Orion."

Proc. Roy. Soc., vol. xxxiii., p. 425. 1882. P. 152.

"On the Spectrum, Visible and Photographic, of the Great Nebula in
Orion." (And Mrs. Huggins.)

Proc. Roy. Soc., vol. xlvi., p. 40. 1889. P. 154.

"Sur le Spectre photographique de la Grande Nébuleuse d'Orion."
Compt. rend., 1889, p. 984.

"Sur le Spectre visible et photographique de la Grande Nébuleuse d'Orion."
Compt. rend., 1890, p. 1310.

"Spectres des Étoiles principales du Trapèze de la Grande Nébuleuse d'Orion."
Compt. rend., October 11, 1897.

"Note in reply to some Observations of Prof. Campbell."
Astronomy and Astrophysics, vol. xiii., p. 568. 1894. P. 174.

"Re-determination of the Principal Line in the Spectrum of the Nebula in Orion, and on the Character of the Line."
Proc. Roy. Soc., vol. xlvi., p. 202. 1890. P. 175.

"Note on the Photographic Spectrum of the Great Nebula in Orion."
Proc. Roy. Soc., vol. xlvi., p. 213. 1890. P. 186.

"Note on the Spectrum of the Great Nebula in Andromeda." P. 189.

HISTORICAL STATEMENT

(From *The Nineteenth Century Review*, June, 1897)

SOON after the completion of the joint work of Dr. Miller and myself, and then working alone, I was fortunate in the early autumn of the same year, 1864, to begin some observations in a region hitherto unexplored; and which, to this day, remain associated in my memory with the profound awe which I felt on looking for the first time at that which no eye of man had seen, and which even the scientific imagination could not foreshow.

The attempt seemed almost hopeless. For not only are the nebulæ very faintly luminous—as Marius put it, “like a rushlight shining through a horn”—but their feeble shining cannot be increased in brightness, as can be that of the stars, neither to the eye nor in the spectroscope, by any optic tube, however great.

Shortly after making the observations of which I am about to speak, I dined at Greenwich, Otto Struve being also a guest; when, on telling of my recent work on the nebulæ, Sir George Airy said, “It seems to me a case of ‘Eyes and No Eyes.’” Such work indeed it was, as we shall see, on certain of the nebulæ.

The nature of these mysterious bodies was still an unread riddle. Towards the end of the last century the elder Herschel, from his observations at Slough, came very near suggesting what is doubtless the true nature, and place in the Cosmos, of the nebulæ. I will let him speak in his own words:

A shining fluid of a nature unknown to us.

What a field of novelty is here opened to our conceptions! . . . We may now explain that very extensive nebulosity, expanded over more than sixty degrees of the heavens, about the constellation of Orion; a luminous matter accounting much better for it than clustering stars at a distance. . . .

If this matter is self-luminous, it seems more fit to produce a star by its condensation, than to depend on the star for its existence.

This view of the nebulæ as parts of a fiery mist out of which the heavens had been slowly fashioned, began, a little before the middle of the present

century, at least in many minds, to give way before the revelations of the giant telescopes which had come into use, and especially of the telescope, six feet in diameter, constructed by the late Earl of Rosse at a cost of not less than £12,000.

Nebula after nebula yielded, being resolved apparently into innumerable stars, as the optical power was increased ; and so the opinion began to gain ground that all nebulæ may be capable of resolution into stars. According to this view, nebulæ would have to be regarded, not as early stages of an evolutional progress, but rather as stellar galaxies already formed, external to our system—cosmical “sandheaps” too remote to be separated into their component stars. Lord Rosse himself was careful to point out that it would be unsafe from his observations to conclude that all nebulosity is but the glare of stars too remote to be resolved by our instruments. In 1858 Herbert Spencer showed clearly that, notwithstanding the Parsonstown revelations, the evidence from the observation of nebulæ up to that time was really in favour of their being early stages of an evolutional progression.

On the evening of August 29, 1864, I directed the telescope for the first time to a planetary nebula in Draco. The reader may now be able to picture to himself to some extent the feeling of excited suspense, mingled with a degree of awe, with which, after a few moments of hesitation, I put my eye to the spectroscope. Was I not about to look into a secret place of creation ?

I looked into the spectroscope. No spectrum such as I expected ! A single bright line only ! At first I suspected some displacement of the prism, and that I was looking at a reflection of the illuminated slit from one of its faces. This thought was scarcely more than momentary ; then the true interpretation flashed upon me. The light of the nebula was monochromatic, and so, unlike any other light I had as yet subjected to prismatic examination, could not be extended out to form a complete spectrum. After passing through the two prisms it remained concentrated into a single bright line, having a width corresponding to the width of the slit, and occupying in the instrument a position at that part of the spectrum to which its light belongs in refrangibility. A little closer looking showed two other bright lines on the side towards the blue, all the three lines being separated by intervals relatively dark.

The riddle of the nebulæ was solved. The answer, which had come to us in the light itself, read : Not an aggregation of stars, but a luminous gas. Stars after the order of our own sun, and of the brighter stars, would give a different spectrum ; the light of this nebula had clearly been emitted by a luminous gas. With an excess of caution, at the moment I did not venture to go further than to point out that we had here to do with bodies of an

order quite different from that of the stars. Further observations soon convinced me that, though the short span of human life is far too minute relatively to cosmical events for us to expect to see in succession any distinct steps in so august a process, the probability is indeed overwhelming in favour of an evolution in the past, and still going on, of the heavenly hosts. A time surely existed when the matter now condensed into the sun and planets filled the whole space occupied by the solar system, in the condition of gas, which then appeared as a glowing nebula, after the order, it may be, of some now existing in the heavens. There remained no room for doubt that the nebulae, which our telescopes reveal to us, are the early stages of long processions of cosmical events, which correspond broadly to those required by the nebular hypothesis in one or other of its forms.

Not, indeed, that the philosophical astronomer would venture to dogmatise in matters of detail, or profess to be able to tell you pat off by heart exactly how everything has taken place in the universe, with the flippant tongue of a Lady Constance after reading "The Revelations of Chaos":

"It shows you exactly how a star is formed; nothing could be so pretty. A cluster of vapour—the cream of the Milky Way; a sort of celestial cheese churned into light."

It is necessary to bear distinctly in mind that the old view which made the matter of the nebulae to consist of an original fiery mist—in the words of the poet :

. . . a tumultuous cloud
Instinct with fire and nitre—

could no longer hold its place after Helmholtz had shown, in 1854, that such an originally fiery condition of the nebulous stuff was quite unnecessary, since in the mutual gravitation of widely separated matter we have a store of potential energy sufficient to generate the high temperature of the sun and stars.

The solution of the primary riddle of the nebulae left pending some secondary questions. What chemical substances are represented by the newly found bright lines? Is solar matter common to the nebulae as well as to the stars? What are the physical conditions of the nebulous matter?

Further observations showed two lines of hydrogen; and recent observations have shown associated with it the new element recently discovered by Professor Ramsay, occluded in certain minerals, and of which a brilliant yellow line in the sun had long been looked upon as the badge of an element as yet unknown. The principal line of these nebulae suggests probably another substance which has not yet been unearthed from its hiding-place in terrestrial rocks by the cunning of the chemist.

Are the nebulæ very hot, or comparatively cool? The spectroscope indicates a high temperature: that is to say, that the individual molecules or atoms, which by their encounters are luminous, have motions corresponding to a very high temperature, and in this sense are very hot. On account of the great extent of the nebulæ, however, a comparatively small number of luminous molecules might be sufficient to make them as bright as they appear to us: taking this view, their mean temperature, if they can be said to have one, might be low, and so correspond with what we might expect to find in gaseous masses at an early stage of condensation.

In the nebulæ I had as yet examined, the condensation of nearly all the light into a few bright lines made the observations of their spectra less difficult than I feared would be the case. It became, indeed, a case of "Eyes and No Eyes" when a few days later I turned the telescope to the Great Nebula in Andromeda. Its light was distributed throughout the spectrum, and consequently extremely faint. The brighter middle part only could be seen, though I have since proved, as I at first suggested might be the case, that the blue and the red ends are really not absent, but are not seen on account of their feebler effect upon the eye. Though continuous, the spectrum did not look uniform in brightness, but its extreme feebleness made it uncertain whether the irregularities were due to certain parts being enhanced by bright lines, or the other parts enfeebled by dark lines.

Out of sixty of the brighter nebulæ and clusters, I found about one-third, including the planetary nebulæ and that of Orion, to give the bright-line spectrum. It would be altogether out of place here to follow the results of my further observations along the same lines of research, which occupied the two years immediately succeeding.

ON THE SPECTRA OF SOME OF THE NEBULÆ

(From *Phil. Trans. Roy. Soc.*, vol. cliv., pp. 437-44, 1864; also, *Phil. Mag.*, vol. xxxi., p. 523)

THE concluding paragraphs of the preceding paper* refer to the similarity of essential constitution which our examination of the spectra of the fixed stars has shown in all cases to exist among the stars, and between them and our sun.

It became, therefore, an object of great importance, in reference to our knowledge of the visible universe, to ascertain whether this similarity of plan observable among the stars, and uniting them with our sun into one great group, extended to the distinct and remarkable class of bodies known as nebulæ. Prismatic analysis, if it could be successfully applied to objects so faint, seemed to be a method of observation specially suitable for determining whether any

* *Spectra of some of the Fixed Stars*, Sec. II., p. 44.

essential physical distinction separates the nebulae from the stars, either in the nature of the matter of which they are composed, or in the conditions under which they exist as sources of light. The importance of bringing analysis by the prism to bear upon the nebulae is seen to be greater by the consideration that increase of optical power alone would probably fail to give the desired information; for, as the important researches of Lord Rosse have shown, at the same time that the number of the clusters may be increased by the resolution of supposed nebulae, other nebulous objects are revealed, and fantastic wisps and diffuse patches of light are seen, which it would be an assumption to regard as due in all cases to the united glare of suns still more remote.

Some of the most enigmatical of these wondrous objects are those which present in the telescope small round or slightly oval disks. For this reason they were placed by Sir William Herschel in a class by themselves under the name of Planetary Nebulae. They present but little indication of resolvability. The colour of their light, which in the case of several is blue tinted with green, is remarkable, since this is a colour extremely rare amongst single stars. These nebulae, too, agree in showing no indication of central condensation. By these appearances the planetary nebulae are specially marked as objects which probably present phenomena of an order altogether different from those which characterise the sun and the fixed stars. On this account, as well as because of their brightness, I selected these nebulae as the most suitable for examination with the prism.

The apparatus employed was that of which a description was given at page 10, Sec. I. A second eyepiece was used in these observations, having a magnifying power of nine diameters. For the greater part of the following observations on the nebulae, the cylindrical lens is not necessary, and was removed from the instrument. The numbers and descriptions of the nebulae, and their places for the epoch 1860, January 0, included within brackets, are taken from the last Catalogue of Sir John Herschel.*

[No. 4373. 37 H. IV. R.A. $17^{\text{h}} 58^{\text{m}} 20^{\text{s}}$. N.P.D. $23^{\circ} 22' 9''$. A planetary nebula; very bright; pretty small; suddenly brighter in the middle, very small nucleus.] In Draco.

On August 29, 1864, I directed the telescope armed with the spectrum apparatus to this nebula. At first I suspected some derangement of the instrument had taken place; for no spectrum was seen, but only a short line of light perpendicular to the direction of dispersion. I then found that the light of this nebula, unlike any other ex-terrestrial light which had yet been subjected by me to prismatic analysis, was not composed of light of different refrangibilities, and therefore could not form a spectrum. A great part of the light from this

* *Phil. Trans.*, Part I., 1864, pp. 1-138.

nebula is monochromatic, and after passing through the prisms remains concentrated in a bright line occupying in the instrument the position of that part of the spectrum to which its light corresponds in refrangibility. A more careful examination with a narrower slit, however, showed that, a little more refrangible than the bright line, and separated from it by a dark interval, a narrower and much fainter line occurs. Beyond this, again, at about three times the distance of the second line, a third, exceedingly faint line was seen. The positions of these lines in the spectrum were determined by a simultaneous comparison of them in the instrument with the spectrum of the induction spark taken between electrodes of magnesium. The strongest line coincides in position with the brightest of the air lines. This line is due to nitrogen, and occurs in the spectrum about midway between *b* and F of the solar spectrum. Its position is seen in fig. 17.*

The faintest of the lines of the nebula agrees in position with the line of hydrogen corresponding to Fraunhofer's F. The other bright line was compared with the strong line of barium 2075 †: this line is a little more refrangible than that belonging to the nebula.

Besides these lines, an exceedingly faint spectrum was just perceived for a short distance on both sides of the group of bright lines. I suspect this is not uniform, but is crossed with dark spaces. Subsequent observations on other nebulae induce me to regard this faint spectrum as due to the solid or liquid matter of the nucleus, and as quite distinct from the bright lines into which nearly the whole of the light from the nebula is concentrated.

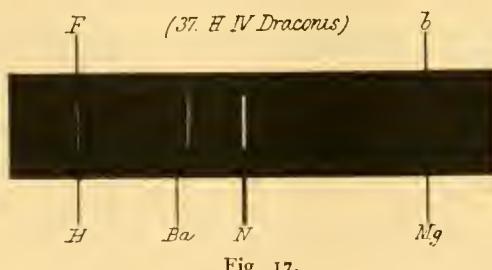


Fig. 17.

In the diagram the three principal lines only are inserted, for it would be scarcely possible to represent the faint spectrum without greatly exaggerating its intensity.

The colour of this nebula is greenish blue.

[No. 4390. 2000 h. Σ 6. R.A. $18^{\text{h}} 5^{\text{m}} 17^{\text{s}}.8$. N.P.D. $83^{\circ} 10' 53''$. A planetary nebula; very bright; very small; round; little hazy.] In Taurus Poniatowskii.

* See also *Phil. Trans.*, 1864, p. 156, and Plate I.

† *Ibid.*, p. 156.

The spectrum is essentially the same as that of No. 4373.

The three bright lines occupy the same positions in the spectrum, which was determined by direct comparison with the spectrum of the induction spark. These lines have also the same relative intensity. They are exceedingly sharp and well defined. The presence of an extremely faint spectrum was suspected. In connection with this it is important to remark that this nebula does not possess a distinct nucleus.

The colour of this nebula is greenish blue.

[No. 4514. 2050 h. 73 H. IV. R.A. $19^{\text{h}} 41^{\text{m}} 7\text{s} \cdot 5$. N.P.D. $39^{\circ} 49' 41'' \cdot 7$. A planetary nebula with a central star. Bright; pretty large; round; star of the 11th magnitude in the middle.] In Cygnus.

The same three bright lines were seen. Their positions in the spectrum were verified by direct comparison with the induction spark. In addition to these a spectrum could be traced from about D to about G of the solar spectrum. This spectrum is much stronger than the corresponding spectrum of 4373. This agrees with the greater brightness of the central star, or nucleus. The opinion that the faint continuous spectrum is formed alone by the light from the bright central point was confirmed by the following observation. When the cylindrical lens was removed, the three bright lines remained of considerable length, corresponding to the diameter of the telescopic image of the nebula; but the faint spectrum became as narrow as a line, showing that this spectrum is formed by light which comes from an object of which the image in the telescope is a point.

Lord Rosse remarks of this nebula, "A very remarkable object, perhaps analogous to H. 450."*

The colour of this nebula is greenish blue.

[No. 4510. 2047 h. 51 H. IV. R.A. $19^{\text{h}} 36^{\text{m}} 3\text{s} \cdot 0$. N.P.D. $104^{\circ} 28' 52'' \cdot 5$. A planetary nebula. Bright; very small; round.] In Sagittarius.

This nebula is less bright than those which have been described. The two brighter of the lines were well defined, and were directly compared with the induction spark. The third line was seen only by glimpses. I had a suspicion of an exceedingly faint spectrum.

The colour of this nebula is greenish blue.

Lord Rosse remarks, "Centre rather dark. The dark part is a little north preceding the middle."†

[No. 4628. 2098 h. 1 H. IV. R.A. $20^{\text{h}} 56^{\text{m}} 31\text{s} \cdot 2$. N.P.D. $101^{\circ} 55' 4'' \cdot 8$. An exceedingly interesting object. Planetary; very bright; small; elliptic.] In Aquarius.

* *Phil. Trans.*, Part III., 1861, p. 733. For a figure of H. 450, see *Phil. Trans.*, 1850, Plate XXXVIII. fig. 15.

† *Ibid.*, 1861, Part III., p. 732.

The three bright lines very sharp and distinct. They were compared for position with the induction spark. Though this object is bright, an indication only of the faint spectrum was suspected. This nebula contains probably a very small quantity of matter condensed into the liquid or solid state.

The colour of the light of this nebula is greenish blue.

Lord Rosse has not detected any central star, nor any perforation, as seen in some of the other planetary nebulae. He represents it with ansæ, which probably indicate a nebulous ring seen edgeways.*

[No. 4447. 2023 h. 57 M. R.A. 18^h 48^m 20^s. N.P.D. 57° 8' 57".2. An annular nebula; bright; pretty large; considerably elongated.] In Lyra.†

The apparent brightness of this nebula, as seen in the telescope, is probably due to its large extent, for the faintness of its spectrum indicates that it has a smaller intrinsic brightness than the nebulae already examined. The brightest of the three lines was well seen. I suspected also the presence of the next in brightness. No indication whatever of a faint spectrum. The bright line looks remarkable, since it consists of two bright dots corresponding to sections of the ring, and between these there was not darkness, but an excessively faint line joining them. This observation makes it probable that the faint nebulous matter occupying the central portion is similar in constitution to that of the ring. The bright line was compared with the induction spark.‡

[No. 4964. 2241 h. 18 H. IV. R.A. 23^h 19^m 9^s.9. N.P.D. 48° 13' 57".5. Planetary; very bright; pretty small, round, blue.]

With a power of 600 this nebula appears distinctly annular. The colour

* *Phil. Trans.*, 1850, p. 507, and Plate XXXVIII. fig. 14.

† Lord Rosse, in his description of this nebula, remarks, "The filaments proceeding from the edge become more conspicuous under increasing magnifying power within certain limits, which is strikingly characteristic of a cluster; still I do not feel confident that it is resolvable.—*Phil. Trans.*, 1844, p. 322, and Plate XIX. fig. 29.

In 1850 Lord Rosse further remarks: "I have not yet sketched it with the 6-feet instrument, because I have never seen it under favourable circumstances: the opportunities of observing it well on the meridian are comparatively rare, owing to twilight. It was observed seven times in 1848, and once in 1849. The only additional particulars I collect from the observations are that the central opening has considerably more nebulosity, and there is one pretty bright star in it, s. f. the centre, and a few other very minute stars. In the sky round the nebula and near it there are several very small stars which were not before seen; and therefore the stars in the dark opening may possibly be merely accidental. In the annulus, especially at the extremities of the minor axis, there are several minute stars, but there was still much nebulosity not seen as distinct stars."—*Phil. Trans.*, 1850, p. 506.

"Nothing additional since 1844, except a star s. f. the middle."—*Phil. Trans.*, 1861, p. 732.

‡ Already in 1850 Lord Rosse had discovered a connection in general plan of structure between some of the nebulae which present small planetary disks in ordinary telescopes, and the annular nebula in Lyra. His words are: "There were but two annular nebulae known in the northern hemisphere when Sir John Herschel's Catalogue was published; now there are seven, as we have found that five of the planetary nebulae are really annular. Of these objects, the annular nebula in Lyra is the one in which the form is the most easily recognised."—*Phil. Trans.*, 1850, p. 506.

of its light is greenish blue.* The spectrum formed by the light from this nebula corresponds with that of 37 H. IV. represented in fig. 17, p. 110.

In the spectrum of this nebula, however, in addition to the three bright lines, a fourth bright line, excessively faint, was seen. This line is about as much more refrangible than the line agreeing in position with F as this line is more refrangible than the brightest of the lines, which coincides with a line of nitrogen.

[No. 4532. 2060 h. 27 M. R.A. $19^{\text{h}} 53^{\text{m}} 29^{\text{s}}\cdot3$. N.P.D. $67^{\circ} 39' 43''$. Very bright; very large; irregularly extended. Dumb-bell.] In Vulpecula.

The light of this nebula, after passing through the prisms, remained concentrated in a bright line corresponding to the brightest of the three lines represented in fig. 17. This line appeared nebulous at the edges. No trace of the other lines was perceived, nor was a faint continuous spectrum detected.

The bright line was ascertained, by a simultaneous comparison with the spectrum of the induction spark, to agree in position with the brightest of the lines of nitrogen.

Minute points of light have been observed in this nebula by Lord Rosse, Otto Struve, and others; the spectra of these bright points, especially if continuous like those of stars, are doubtless invisible from excessive faintness.

By suitable movements given to the telescope, different portions of the image of the nebula formed in the telescope were caused successively to fall upon the opening of the slit, which was about $\frac{1}{10}$ inch by $\frac{1}{300}$ inch. This method of observation showed that the light from different parts of the nebula is identical in refrangibility, and varies alone in degree of intensity.

In addition to these objects the following were also observed:—

[No. 4294. 92 M. R.A. $17^{\text{h}} 12^{\text{m}} 56^{\text{s}}\cdot9$. N.P.D. $46^{\circ} 43' 31''\cdot2$.] In Hercules. Very bright globular cluster of stars. The bright central portion was brought upon the slit. A faint spectrum similar to that of a star. The light could be traced from between C and D to about G.

Too faint for the observation of lines of absorption.

[No. 4244. 50 H. IV. R.A. $16^{\text{h}} 43^{\text{m}} 6^{\text{s}}\cdot4$. N.P.D. $42^{\circ} 8' 38''\cdot8$. Very bright; large; round.] In Hercules. The spectrum similar to that of a faint star. No indication of bright lines.

[No. 116. 50 h. 31 M. R.A. $0^{\text{h}} 35^{\text{m}} 3^{\text{s}}\cdot9$. N.P.D. $49^{\circ} 29' 45''\cdot7$.] The brightest part of the Great Nebula in Andromeda was brought upon the slit.

The spectrum could be traced from about D to F. The light appeared

* For Lord Rosse's observations of this nebula, see *Phil. Trans.*, 1844, p. 323; *ibid.*, 1850, p. 507, and Plate XXXVIII. fig. 13; *ibid.*, 1861, p. 736, and Plate XXX. fig. 40.

to cease very abruptly in the orange; this may be due to the smaller luminosity of this part of the spectrum. No indication of the bright lines.

[No. 117. 51 h. 32 M. R.A. $0^h 35^m 5^s.3$. N.P.D. $49^\circ 54' 12''$. Very, very bright; large; round; pretty suddenly much brighter in the middle.]

This small but very bright companion of the Great Nebula in Andromeda presents a spectrum apparently exactly similar to that of 31 M.

The spectrum appears to end abruptly in the orange; and throughout its length is not uniform, but is evidently crossed either by lines of absorption or by bright lines.

[No. 428. 55 Androm. R.A. $1^h 44^m 55^s.9$. N.P.D. $49^\circ 57' 41''$. Fine nebulous star with strong atmosphere.] The spectrum apparently similar to that of an ordinary star.*

[No. 826. 2618 h. 26 IV. R.A. $4^h 7^m 50^s.8$. N.P.D. $103^\circ 5' 32''$. Very bright cluster.] In Eridanus. The spectrum could be traced from the orange to about the blue. No indication of the bright lines.

Several other nebulæ were observed, but of these the light was found to be too faint to admit of satisfactory examination with the spectrum apparatus.

It is obvious that the nebulæ 37 H. IV., 6 Σ., 73 H. IV., 51 H. IV., 1 H. IV., 57 M., 18 H. IV. and 27 M. can no longer be regarded as aggregations of suns after the order to which our own sun and the fixed stars belong. We have in these objects to do no longer with a special modification only of our own type of suns, but find ourselves in the presence of objects possessing a distinct and peculiar plan of structure.

In place of an incandescent solid or liquid body transmitting light of all refrangibilities through an atmosphere which intercepts by absorption a certain number of them, such as our sun appears to be, we must probably regard these objects, or at least their photo-surfaces, as enormous masses of luminous gas or vapour. For it is alone from matter in the gaseous state that light consisting of certain definite refrangibilities only, as is the case with the light of these nebulæ, is known to be emitted.

It is indeed *possible* that suns endowed with these peculiar conditions of luminosity may exist, and that these bodies are clusters of such suns. There are, however, some considerations, especially in the case of the planetary nebulæ, which are scarcely in accordance with the opinion that they are clusters of stars.

Sir John Herschel remarks of one of this class, in reference to the absence of central condensation: "Such an appearance would not be presented by a globular space uniformly filled with stars or luminous matter, which structure

* "Looked at eight times, but saw no nebulous atmosphere."—Lord Rosse, *Phil. Trans.*, 1861, p. 712.

would necessarily give rise to an apparent increase of brightness towards the centre in proportion to the thickness traversed by the visual ray. We might therefore be inclined to conclude its real constitution to be either that of a hollow spherical shell or of a flat disk presented to us (by a highly improbable coincidence) in a plane precisely perpendicular to the visual ray."* This absence of condensation admits of explanation, without recourse to the supposition of a shell or of a flat disk, if we consider them to be masses of glowing gas. For supposing, as we probably must do, that the whole mass of the gas is luminous, yet it would follow, by the law which results from the investigations of Kirchhoff, that the light emitted by the portions of gas beyond the surface visible to us would be in great measure, if not wholly, absorbed by the portion of gas through which it would have to pass, and for this reason there would be presented to us a *luminous surface* only.†

Sir John Herschel further remarks ‡: "Whatever idea we may form of the real nature of the planetary nebulae, which all agree in the absence of central condensation, it is evident that the intrinsic splendour of their surfaces, *if continuous*, must be almost infinitely less than that of the sun. A circular portion of the sun's disk, subtended an angle of 1', would give a light equal to that of 780 full moons, while among all the objects in question there is not one which can be seen with the naked eye." The small brilliancy of these nebulae is in accordance with the conclusions suggested by the observations of this paper; for, reasoning by analogy from terrestrial physics, glowing or luminous gas would be very inferior in splendour to incandescent solid or liquid matter.

Such gaseous masses would be doubtless, from many causes, unequally dense in different portions; and if matter condensed into the liquid or solid state were also present, it would, from its superior splendour, be visible as a bright point or points within the disk of the nebula. These suggestions are in close accordance with the observations of Lord Rosse.

Another consideration which opposes the notion that these nebulae are clusters of stars is found in the extreme simplicity of constitution which the

* "Outlines of Astronomy," 7th edit., p. 646.

† Sir William Herschel in 1811 pointed out the necessity of supposing the matter of the planetary nebulae to have the power of intercepting light. He wrote: "Admitting that these nebulae are globular collections of nebulous matter, they could not appear equally bright if the nebulosity of which they are composed consisted only of a luminous substance perfectly penetrable to light. . . . Is it not rather to be supposed that a certain high degree of condensation has already brought on a sufficient consolidation to prevent the penetration of light, which by this means is reduced to a superficial planetary appearance?"

"Their planetary appearance shows that we only see a superficial lustre such as opaque bodies exhibit, and which could not happen if the nebulous matter had no other quality than that of shining, or had so little solidity as to be perfectly transparent."—*Phil. Trans.*, 1811, pp. 314, 315.

‡ "Outlines of Astronomy," 7th edit., p. 646.

three bright lines suggest, whether or not we regard these lines as indicating the presence of nitrogen, hydrogen, and a substance unknown.

It is perhaps of importance to state that, except nitrogen, no one of thirty of the chemical elements the spectra of which I have measured has a strong line very near the bright line of the nebulæ. If, however, this line were due to nitrogen we ought to see other lines as well; for there are specially two strong double lines in the spectrum of nitrogen, one at least of which, if they existed in the light of the nebulæ, would be easily visible.* In my experiments on the spectrum of nitrogen, I found that the character of the brightest of the lines of nitrogen, that with which the line in the nebulæ coincides, differs from that of the two double lines next in brilliancy. This line is more nebulous at the edges, even when the slit is narrow and the other lines are thin and sharp. The same phenomenon was observed with some of the other elements.† We do not yet know the origin of this difference of character observable among lines of the same element. May it not indicate a physical difference in the atoms, in connection with the vibrations of which the lines are probably produced? The speculation presents itself, whether the occurrence of this one line only in the nebulæ may not indicate a form of matter more elementary than nitrogen, and which our analysis has not yet enabled us to detect.

Observations on other nebulæ which I hope to make may throw light upon these and other considerations connected with these wonderful objects.

ON THE SPECTRUM OF THE GREAT NEBULA IN THE SWORD-HANDLE OF ORION

(From *Proc. Roy. Soc.*, vol. xiv., p. 39, 1865; also *Month. Not.*, vol. xxv., p. 155)

IN a paper recently presented to the Royal Society,‡ I gave the results of the application of prismatic analysis to some of the objects in the heavens known as nebulæ. Eight of the nebulæ examined gave a spectrum indicating gaseity, and, of these, six belong to the class of small and comparatively bright objects which it is convenient to distinguish still by the name of planetary. These nebulæ present little indication of probable resolvability into discrete points,

* *Phil. Trans.*, 1864, p. 154, and Plate I.

For the purpose of ascertaining whether the absence of the other bright lines of nitrogen might be connected with the presence of hydrogen, I arranged an apparatus in which, while the spectrum of the induction-spark in a current of nitrogen was being observed, a current of hydrogen could be introduced, and the proportion of the two gases to each other easily regulated. With this apparatus the fading out of the bright lines of nitrogen, as the proportion of this gas to hydrogen was diminished, and again their increase in brilliancy when the current of nitrogen was made stronger, were carefully observed, but without detecting any marked variation in the relative brightness of the lines.

† *Ibid.*, 1864, pp. 143, 150.

‡ "On the Spectra of some of the Nebulæ," *Phil. Trans.*, 1864, p. 437. (See preceding Paper.)

even with the greatest optical power which has yet been brought to bear upon them.

The other two nebulae which gave a spectrum indicative of matter in the gaseous form are 57 M, the annular nebula in Lyra, and 27 M, the Dumb-bell nebula. The results of the examination of these nebulae with telescopes of great power must probably be regarded as in favour of their consisting of clustering stars. It was therefore of importance to determine, by the observation of other objects, whether any nebulae which had been *certainly resolved* into stars gave a spectrum which shows the source of light to be glowing gas. With this purpose in view I submitted the light of the following easily resolved clusters to spectrum analysis :

" 4670. 2120 h. 15 M. Very bright cluster; well resolved." *

" 4678. 2125 h. 2 M. Bright cluster, well resolved."

Both these clusters gave a continuous spectrum.

I then examined the Great Nebula in the Sword-handle of Orion. The results of telescopic observation on this nebula † seem to show that it is suitable for observation as a crucial test of the correctness of the usually received opinion that the resolution of a nebula into bright stellar points is a certain and trustworthy indication that the nebula consists of discrete stars after the order of those which are bright to us. Would the brighter portions of the nebula adjacent to the trapezium, which have been resolved into stars, present the same spectrum as the fainter and outlying portions? In the brighter parts, would the existence of closely aggregated stars be revealed to us by a continuous spectrum, in addition to that of the true gaseous matter?

The telescope and spectrum apparatus employed were those of which a description was given in my paper already referred to.

The light from the brightest parts of the nebula near the trapezium was resolved by the prisms into three bright lines, in all respects similar to those of the gaseous nebulae, and which are described in my former paper.

These three lines, indicative of gaseity, appeared (when the slit of the apparatus was made narrow) very sharply defined and free from nebulosity; the intervals between the lines were quite dark.

* The numbers and descriptions are from Sir John Herschel's Catalogue, *Phil. Trans.*, 1864, Part I.

† "The general aspect of the less luminous and cirrous portion is simply nebulous and irresolvable; but the brighter portion immediately adjacent to the trapezium forming the square front of the head, is shown with the 18-inch reflector broken up into masses, whose mottled and curdling light evidently indicates, by a sort of granular texture, its consisting of stars, and when examined under the great light of Lord Rosse's reflector, or the exquisite defining power of the great achromatic at Cambridge, U.S., is evidently perceived to consist of clustering stars. There can therefore be little doubt as to the whole consisting of stars too minute to be discerned individually even with these powerful aids, but which become visible as points of light when closely adjacent in the more crowded parts. . ."—Sir John Herschel, *Outlines of Astronomy*, 7th edition, pp. 651, 652.

When either of the four bright stars, α , β , γ , δ Trapezii was brought upon the slit, a continuous spectrum of considerable brightness, and nearly linear (the cylindrical lens of the apparatus having been removed), was seen, together with the bright lines of the nebula, which were of considerable length, corresponding to the length of the opening of the slit. The fifth star γ' and the sixth α' are seen in the telescope, but the spectra of these are too faint for observation.

The positions in the spectra of α , β , γ , δ Trapezii, which correspond to the positions in the spectrum of the three bright lines of the nebula, were carefully examined, but in no one of them were dark lines of absorption detected.

The part of the continuous spectra of the stars α , β , γ , near the position in the spectrum of the brightest of the bright lines of the nebula, appeared on a simultaneous comparison to be more brilliant than the line of the nebula, but in the case of γ the difference in brightness was not great. The corresponding part of δ was perhaps fainter. In consequence of this small difference of brilliancy, the bright lines of the adjacent nebula appeared to cross the continuous spectra of γ and δ Trapezii.

Other portions of the nebula were then brought successively upon the slit; but throughout the whole of those portions of the nebula which are sufficiently bright for this method of observation the spectrum remained unchanged, and consisted of the three bright lines only. The whole of this Great Nebula, as far as it lies within the power of my instrument, emits light which is identical in its characters; the light from one part differs from the light of another in intensity alone.

The clustering stars of which, according to Lord Rosse and Professor Bond, the brighter portions of this nebula consist, cannot be supposed to be invisible in the spectrum apparatus because of their faintness, an opinion which is probably correct of the minute and widely separated stars seen in the Dumb-bell Nebula, and to which reference was made in my former paper. The evidence afforded by the largest telescopes appears to be that the brighter parts of the nebula in Orion consist of a "mass of stars"; the whole, or the greater part of the light from this part of the nebula must therefore be regarded as the united radiation of these numerous stellar points. Now it is this light which, when analysed by the prism, reveals to us its gaseous source, and the bright lines indicative of gaseity are free from any trace of a continuous spectrum, such as that exhibited by all the brighter stars which we have examined.

The conclusion is obvious, that the detection in a nebula of minute closely associated points of light, which has hitherto been considered as a certain indication of a stellar constitution, can no longer be accepted as a trustworthy

proof that the object consists of true stars. These luminous points, in some nebulae at least, must be regarded as themselves gaseous bodies, denser portions, probably, of the great nebulous mass, since they exhibit a constitution which is identical with the fainter and outlying parts which have not been resolved. These nebulae are shown by the prism to be immense gaseous systems; and the conjecture appears probable that their apparent permanence of general form is maintained by the continual motions of these denser portions which the telescope reveals as lucid points.

The opinions which have been entertained of the enormous distances of the nebulae, since these have been founded upon the supposed extent of remoteness at which stars of considerable brightness would cease to be separately visible in our telescope, must now be given up in reference at least to those of the nebulae the matter of which has been established to be gaseous.

It is much to be desired that *proper motion* should be sought for in those of the nebulae which are suitable for this purpose; indications of parallax might possibly be detected in some, if any nebulae could be found that would admit of this observation.

If this view of the greater nearness to us of the gaseous nebulae be accepted, the magnitudes of the separate luminous masses which the telescope reveals as minute points, and the actual intervals existing between them, would be far less enormous than we should have to suppose them to be on the ordinary hypothesis.

It is worthy of consideration that all the nebulae which present a gaseous spectrum exhibit the *same three bright lines*; in one case only, 18 H. IV., was a fourth line seen. If we suppose the gaseous substance of these objects to represent the "nebulous fluid" out of which, according to the hypothesis of Sir Wm. Herschel, stars are to be elaborated by subsidence and condensation, we should expect a gaseous spectrum in which the groups of bright lines were as numerous as the dark lines due to absorption which are found in the spectra of the stars. Moreover, if the improbable supposition be entertained, that the three bright lines indicate matter in its most elementary forms, still we should expect to find in some of the nebulae, or in some parts of them, a more advanced state towards the formation of a number of separate bodies, such as exist in our sun and in the stars; and such an advance in the process of formation into stars would have been indicated by a more complex spectrum.

My observations, as far as they extend at present, seem to be in favour of the opinion that the nebulae which give a gaseous spectrum are systems possessing a structure, and a purpose in relation to the universe, altogether distinct and of another order from the great group of cosmical bodies to which our sun and the fixed stars belong.*

* See Note on p. 60.

The nebulous star ι Orionis was examined, but no peculiarity could be detected in its continuous spectrum.*

FURTHER OBSERVATIONS ON THE SPECTRA OF SOME OF THE NEBULÆ, WITH A MODE OF DETERMINING THE BRIGHTNESS OF THESE BODIES

(From *Phil. Trans.*, vol. clvi., p. 381, 1866. Also *Phil. Mag.*, vol. xxxi., p. 475)

In my former papers, "On the Spectra of some of the Nebulæ,"† and "On the Spectrum of the Great Nebula in Orion,"‡ I described the results of a prismatic examination of the light of some of the objects in the heavens which have been classed together under the common denomination of Nebulæ. The present paper contains the results of the application of the same method of research, with the same apparatus, to the light of others of the same class of bodies. To these observations with the prism are appended the results of an attempt to determine the intrinsic intensity of the light emitted by some of the nebulae which give a spectrum indicating gaseity.

On account of the great faintness of the light of most of the objects described in this paper, I have not found it possible to determine more than the general characters of the spectra which they form in the instrument. The present observations confirm the results which I have already presented to the Royal Society—namely, that with my instrument clusters and nebulae give either a spectrum which is apparently continuous, or a spectrum consisting of one, two, or three bright lines.

The description "continuous spectrum" in this paper and in my former papers must not be understood to mean more than that when the slit was made as narrow as the feeble light of the object permitted, the spectrum was not resolved into bright lines. Whether the continuous spectrum was in any case interrupted by dark lines in a manner similar to the spectra of the sun and fixed stars, I was not able to ascertain; for when the feeble light of a nebula is dispersed by the prism into a spectrum consisting of light of all refrangibilities, the spectrum is extremely faint and difficult of examination. Before the slit is made sufficiently narrow for the detection of dark or bright lines, the spectrum becomes, in the case of nearly all the objects examined, too faint to be visible. When, however, a nebula is observed the light of which is monochromatic, or nearly so, the one, two, or three bright lines in which the light remains

* Admiral Smyth appears to have always maintained that the results of telescopic observation on the nebulae were insufficient to support the opinion that all these objects were probably of stellar constitution. See his "Cycle of Celestial Objects," vol. i., p. 316; and his "Speculum Hartwellianum," pp. 111–114.

† *Phil. Trans.*, 1864, p. 437. P. 108.

‡ *Proc. Roy. Soc.*, vol. xiv., p. 39. P. 116.

concentrated can usually be seen when the slit is made narrow. Some of these nebulae have been examined with a slit not exceeding $\frac{1}{300}$ th of an inch in width.

[A conclusion of some importance to our interpretation of the phenomena of these bodies, and especially of value in reference to the theoretical views we may form of the relation of the gaseous nebulae to the other nebulae and clusters, presents itself in connection with these observations. The intensity of the brightest line of the gaseous nebulae is in most cases greater than the intensity of the light of the *same refrangibility* of those nebulae and clusters which furnish a spectrum which is apparently continuous. The superior intensity of the light may indicate a more intense heat. It may be, therefore, that of all the objects usually classed under the denomination of nebulae and clusters, those which give a gaseous spectrum are, as a class, to be regarded as the *hottest*.—June 1866.]

The continuous spectra of some of the nebulae and clusters are irregularly bright in some parts of the spectrum; but when the width of the slit was reduced, the bright portions did not appear to become more defined, as would be the case with a spectrum containing bright lines.* This irregularity of brightness may perhaps be due in some cases to the probable mode of formation of these continuous spectra. In the case, at least, of the clusters which the telescope resolves into stellar points, the spectrum must be composed of the blending together of the spectra of the constituent bright points. Now it is not improbable that these component spectra, like the spectra of the stars, differ from each other in the relative brightness of their different parts.

The positions in the spectrum of the bright lines of the gaseous nebulae described in my former paper were determined by a simultaneous comparison in the instrument of these lines with the bright lines of nitrogen, hydrogen, and barium. The bright lines of the gaseous nebulae referred to in this paper were not compared directly with any terrestrial spectra, partly because of the great

* The peculiar appearance of the continuous spectra of some of the nebulae and clusters has suggested to me, from my first examination of them, that possibly the luminous points into which the telescope resolves some of these objects may not be of the same nature as the true stars. My observations of the Great Nebula in Andromeda and of its small but bright companion in August 1864, were recorded thus: "The spectrum appears to end abruptly in the orange; and throughout its length is not uniform, but is evidently crossed either by lines of absorption or by bright lines" (*Phil. Trans.*, 1864, p. 442). [The same characters have since been found in several of the brighter nebulae and clusters. It is possible to explain the absence of the less refrangible rays, which are wanting in these spectra, by supposing them to have been intercepted by absorbent vapours. The apparently *complete* want of light in this part of the spectrum, and the unequal, mottled appearance of the brighter parts of the spectrum, suggest rather that the light may have emanated from a gaseous source, and that the spectrum consists of numerous *bright* lines. The faintness of these spectra has prevented me from using a slit sufficiently narrow for the determination of their true nature. Some quite recent observations, which are not yet complete, appear to support the view that the bright points of some clusters may possess a physical constitution which is not analogous to that of the sun and the brighter of the separate stars.—June 1866.]

faintness of most of these objects, and partly because the former comparisons were found to be injuriously fatiguing to the eye.

The value of this application of spectrum analysis appears to me to consist chiefly in the assistance which this method of observation may afford us in ascertaining the true nature of the nebulae, and the relation which they sustain to the other orders of the heavenly bodies. I have therefore added to my prismatic observations such of the results of former telescopic observations as, in my opinion, would be of assistance to an understanding of the proper significance of the new information furnished by the prism.

[Although the detection in a nebula by the telescope of closely associated points of light can no longer be regarded as a trustworthy indication that the object consists of true stars, yet it is of importance to ascertain how far the classification of the nebulae by the prism corresponds with the telescopic indications of their resolvability. I have Lord Rosse's permission to state that the matter of the Great Nebula in Orion, which the prism shows to be gaseous, has not been resolved by his telescope. In some parts of the nebula he observed a large number of exceedingly minute *red* stars. These red stars, however, though apparently connected with the irresolvable blue material of the nebula, yet seem to be distinct from it. The light of these stars is doubtless too feeble to furnish a visible spectrum.

Lord Oxmantown has examined all the observations made at Parsonstown of those nebulae which I have subjected to prismatic examination. My list contained 41 nebulae which give a continuous spectrum, and 19 gaseous nebulae. Lord Oxmantown finds that these nebulae may be arranged thus:—

		Continuous spectrum.	Gaseous spectrum.
Clusters	.	10	0
Resolved, or resolved?	:	5	0
Resolvable, or resolvable?	:	10	6
{ Blue, or green, no resolvability	:	0	4
{ No resolvability seen	:	6	5
Total observed	:	31	15
Not observed	:	10	4
		41	19
— June, 1866.]			

The numbers and descriptions of the nebulae, and their places for the epoch 1860.0, included within brackets, are taken from Sir John F. W. Herschel's "General Catalogue of Nebulae and Clusters of Stars."*

OBSERVATIONS OF NEBULÆ THE SPECTRA OF WHICH INDICATE GASEITY

[No. 2102. 3248 h. 27 H. IV. R.A. $10^h 18^m 2^s.2$. N.P.D. $107^\circ 55' 50''$. A planetary nebula. Very bright; little extended; position of longer dimension 135° ; diameter = $32'' \pm$; blue.]

* *Phil. Trans.*, 1864, pp. 1-137.

This nebula was observed on April 25, 1865, with a silvered glass reflector. The spectrum consisted of one bright line about midway between *b* and *F* of the solar spectrum, and probably corresponding in position to the brightest of the lines of nitrogen.

In consequence of the imperfect adjustment, at this time, of the reflector, I was unable to ascertain satisfactorily whether any other fainter lines were also present in the spectrum.

Sir John Herschel describes its appearance as "somewhat hazy, with a slight nebulous atmosphere." *

D'Arrest's measures of the diameter—January 13, 1856, = 25", and March 11, 1856, = 27".†

[On March 14, 1866, I examined this nebula with my refractor of 8 inches aperture. Powers of 600 and 920 diameters showed that the nebula is annular. It appears to consist of an oval ring of brighter matter surrounded by a broad margin of faint nebulosity. The area enclosed by the ring, like that of the annular nebula in Lyra, is filled with faintly luminous matter. The faint nebulosity surrounding the ring appears circular, or nearly so, suggesting that the ring, seen obliquely from our system, exists within a globular mass of faint nebulous material.

When the spectroscope was applied, in addition to the bright line seen in 1865, the two other bright lines which are present in many nebulae were also observed. When the slit was made sufficiently narrow for these bright lines to appear defined, no trace of a continuous spectrum was detected. With a wide slit, however, I *suspected* a faint and broad continuous spectrum.—June 1866.]

[No. 4234. 1970 h. 5 Σ. R.A. 16^h 38^m 36^s. N.P.D. 65° 56' 10". A planetary nebula; very bright; very small; disk and border.]

I observed this nebula, and all the objects which follow in this paper, with my refractor of 8 inches aperture.

On this nebula powers up to 1000 diameters were employed. With low powers this object appeared small, round, intensely bright, and decidedly blue in colour. Higher powers showed a uniform disk surrounded with a faint nebulous halo.

The prism resolves the light of this nebula into three bright lines, occupying the same positions in the spectrum as the bright lines of nebula No. 4373.‡ The two brightest lines are bright, and differ not very greatly in intensity; the less refrangible of the lines is the brighter. The most refrangible of the three lines is much fainter than the others.

* "Results of Astronomical Observations at the Cape of Good Hope," p. 94, and Plate VI. fig. 5.

† "Resultate aus Beobachtungen der Nebelflecken und Sternhaufen," p. 326.

‡ *Phil. Trans.*, 1864, p. 438.

A very faint continuous spectrum was seen by glimpses.

Lord Rosse describes this nebula: "Intense blue centre fading off to some distance all around. I found once or twice there were projections. (N.B. The existence of these not satisfactorily proved.") *)

Sir John Herschel gives its diameter = 8".†

D'Arrest's measures of its diameter are—1856, March 12, = 6", June 1, = 8".‡

[No. 4403. 2008 h. 17 M. R.A. 18^h 12^m 33^s. N.P.D. 106° 13' 36". Remarkable object. Bright; extremely large; extremely irregular figure; 2-hooked.]

Sir John Herschel observes of this nebula: "A most curious object, not unlike the nebula of Orion (as it used to be figured like a Greek capital omega, Ω). There is in it a resolvable portion § or knot distinctly separated from and insulated in the rest, as if it had absorbed the nebula near it. Its form is like the Greek Ω, with the left (or following) base-line turned upwards. The curved or horseshoe part is very faint, and has many stars in it; the preceding base-line hardly visible. Its light is not equable, but blotty." ||

Lord Oxmantown informs me that in the observations of this nebula at Birr Castle there is no mention of resolvability; and that "the central part to the right of star α consists of bunches or patches of bright nebulosity, with fainter nebulosity intervening."

The spectrum of this nebula indicates that it possesses a gaseous constitution. One bright line only was seen, occupying in the spectrum apparently the same position as the brightest of the lines of nitrogen. When the slit was made as narrow as the intensity of the light would permit, this bright line was not so well defined as the corresponding line in some of the other nebulae under similar conditions of the slit, but remained nebulous at the edges.

When the brightest portion of the nebula containing the nucleus or "bright knot" was brought upon the slit, in addition to the bright line a faint narrow continuous spectrum was seen.

The bright knot appeared in my telescope smaller and more condensed than it is represented in the drawings of Sir John Herschel.

[No. 4572. 2075 h. 16 H. IV. R.A. 20^h 16^m 7^s.9. N.P.D. 70° 20' 19".3. A planetary nebula; bright; pretty small; round; four stars near.]

"Rather hazy at the edges, but not materially brighter in the middle,

* *Phil. Trans.*, 1861, p. 732.

† *Ibid.*, 1833, p. 458.

‡ "Beobachtungen der Nebelflecken und Sternhaufen," p. 341.

§ "Mr. Mason declares the upper and larger knot to be irresolvable by his telescope (a reflector of 12 inches aperture and 14 feet focal length). In this particular my observations of 1835 and 1837 so far agree, that its resolvability is not mentioned in words or indicated in the diagrams made on those occasions."—Sir John Herschel, "Results of Astronomical Observations at the Cape of Good Hope," p. 7, and Plate II. fig. 1.

|| *Phil. Trans.*, 1833, p. 461, and Plate XII. fig. 35.

but no hollow. It has four stars near it like satellites. Diameter in R.A. $30'' \pm$. Its light is a little mottled, but it is well defined." *

Lord Rosse remarks: "This planetary nebula is a beautiful little spiral. Star or bright nucleus north following the middle." †

"Dieser Nebel hat sich seit 30 Jahren bestimmt nicht nachweisbar bewegt. Klein aber ziemlich hell, $25''$ diam., rund und durchaus gleichförmig hell; erscheint in der That wie eine Nebelscheibe."—D'Arrest.‡

"Durchmesser gemessen = $27''$."—Schultz.§

The spectrum of this nebula consisted of one bright nebulous line of the same refrangibility as the brightest of the lines of nitrogen. No other lines were *certainly* seen.

The three brighter of the enclosing stars gave the usual stellar continuous spectrum.

Sir John Herschel remarks of these stars near the nebula, "The point to which I would draw attention is the frequent and close proximity to these objects (the planetary nebulae) of minute stars, which suggest the idea of accompanying satellites." ||

D'Arrest, referring to these small stars, says (in 1856): "Von den Satelliten der planetarischen Nebelflecken die wiedergesehenen standen noch unverrückt in den von Sir J. Herschel so sorgfältig bestimmten Stellungen, oder können sich im Laufe der letzten Vierteljahrhunderts nur sehr kleine Größen daraus entfernt haben. . . . Von etwa dritthalb Hundert Nebeln lässt es sich sehr wahrscheinlich machen, dass eigene jährliche Bewegungen im Betrage von mehr als einer Bogensekunde nicht vorhanden sind. Streng beweisen endlich lässt sich vollständige Unmerklichkeit der Eigenbewegung während der letzten 60 Jahre bei einigen unter den planetarischen Nebelflecken." ¶

* *Phil. Trans.*, 1833, p. 467, and Plate XIII. fig. 47.

† *Ibid.*, 1861, p. 733, and Plate XXVII. fig. 34.

‡ "Beobachtungen der Nebelflecken und Sternhaufen," p. 349.

§ *Astron. Nachrichten*, No. 1541. || *Phil. Trans.*, 1833, p. 500.

¶ "Beobachtungen der Nebelflecken und Sternhaufen," p. 308.

Some observers describe indications of the occurrence of continual and very rapid variations in the light of some of the gaseous nebulae. It must not be forgotten, however, that in the nebulae only phenomena of enormous magnitude could be visible to us. Besides this consideration, in the constantly varying state of our atmosphere, and in the variation in the power of the eye to appreciate minute differences of relative brightness when the conditions of illumination of the object are different, we have probably a sufficient explanation of these phenomena.

M. O. Struve (in 1856) says: ". . . the general impression that I have derived from the observations of this year has been that the central part of the nebula of Orion is in a state of continual change with regard to the brightness in different parts of it. Even with the best definition, its appearances were to me on no evening entirely agreeing with those on the next or any other night."—*Monthly Notices Royal Astron. Soc.*, vol. xvii., p. 230.

Dr. A. Schultz (in 1865) observes of No. 4234, 1970 h., "Der Nebel flammt nicht in gewöhnlicher Weise, zeigt aber eine unaufhörlich gleichmässige Dilatation und Contraction." And also of No. 4572, 2075 h., "Momentan verschwindet die Nebulosität ganz (?) und der Nebel zeigt sich wie eine sehr reicher gedrängter Sternhaufen."—*Astron. Nachrichten*, No. 1541.

[No. 4499. 2043 h. 38 H. VI. R.A. $19^{\text{h}} 24^{\text{m}} 53^{\text{s}}$. N.P.D. $81^{\circ} 3' 37''$. Considerably bright; small; irregularly round; well resolved.]

"A very small roundish cluster, 40" diam., of very small stars, one brighter than the rest. It is like a nebula well resolved, and is a curious object. . . . Doubtful if a resolved cluster, or a nebula of the first class."—Sir John Herschel.*

"Four stars in nebula, and two more on preceding edge."—Lord Rosse.†

"Suspect more smaller stars."‡—Lord Oxmantown.

The spectrum of this nebula, or at least of some parts of it, is almost certainly of the order which indicates that the source of the light is gaseous matter. I believe that the spectrum consists of one bright line. The object, however, is very faint, and the determination of its spectrum with my instrument very difficult. I examined the light of this nebula several times, with eyepieces of different powers applied to the small telescope of the spectroscope, but in all the observations I was confirmed in the opinion that the greater part at least of the light is monochromatic.

Probably there is, in addition to the bright line or lines, a faint continuous spectrum, which may belong to the stars which are visible within the nebula.

[No. 4827. 2178 h. 705 H. II. R.A. $22^{\text{h}} 35^{\text{m}} 6^{\text{s}}\cdot6$. N.P.D. $29^{\circ} 27' 5''$. Bright; small; round; gradually very little brighter in the middle; easily resolvable.]

"Planetary?"—Lord Rosse. §

"Three stars preceding. Resolvable?"—Lord Oxmantown.

One bright line only was distinctly seen in the spectroscope.

On account of the faintness of the object, I am unable to say whether any other fainter lines are also present, or a faint continuous spectrum.

[No. 4627. 2099 h. 192 H. I. R.A. $20^{\text{h}} 56^{\text{m}} 17^{\text{s}}\cdot5$. N.P.D. $35^{\circ} 59' 39''$. Considerably bright; large; barely resolvable; two stars attached.]

"Has an appearance of two nuclei or points of greatest condensation; it touches a fine double star."—Sir John Herschel. ||

"The nebula has three knots in it."—Lord Rosse. ¶

"No mention of resolvability."—Lord Oxmantown.

The different knots of this nebula give a spectrum indicating gaseity, though in the examination of some parts of the nebula I suspected the presence of a faint continuous spectrum as well. The continuous spectrum may possibly belong to the small stars which are represented in Lord Rosse's drawing of this object.

* *Phil. Trans.*, 1833, p. 464.

† *Ibid.*, 1861, p. 732.

‡ This observation, and those of other nebulae to which the name of Lord Oxmantown is attached, have been kindly extracted for me from the observations made at Birr Castle.

§ *Phil. Trans.*, 1861, p. 735.

|| *Ibid.*, 1833, p. 469.

¶ *Ibid.*, 1861, p. 734, and Plate XXX. fig. 37.

One bright line only was distinctly seen, of apparently the same refrangibility as the brightest of the nitrogen line. This bright line appeared by glimpses to be double. Possibly this appearance was due to the presence near it of a second line. The faintness of the light did not permit the slit to be made sufficiently narrow for the determination of this point.

[[No. 385. 76 M. R.A. $1^h 33^m 28^s \cdot 5$. N.P.D. $39^\circ 8' 52'' \cdot 4$. Very bright ; preceding of double nebula.]

[No. 386. 193 H. I. R.A. $1^h 33^m 37^s \cdot 5$. N.P.D. $39^\circ 7' 27'' \cdot 4$. Very bright ; following of double nebula.]

Both parts of this double nebula give a gaseous spectrum. The brightest only of the three lines usually present was *certainly* seen. The second line is probably also present.

I suspected a faint continuous spectrum at the preceding edge of No. 386.

[No. 2343. 838 h. 97 M. R.A. $11^h 6^m 34^s \cdot 8$. N.P.D. $34^\circ 13' 38'' \cdot 2$. Planetary ; very bright ; very large ; round ; very gradually, very suddenly brighter in the middle.]

"A large uniform nebulous disk, diameter $19^s \cdot 0$ in R.A. Quite round, very bright, not sharply defined, but yet very suddenly fading away to darkness."

—Sir John Herschel.*

"Two stars considerably apart in the central region, dark penumbra round each spiral arrangement, with stars as apparent centres of attraction. Stars sparkling in it ; resolvable."—Lord Rosse.†

"Two stars were easily seen in this nebula formerly ; since 1850 only one has been seen. Not observed since April 1864."—Lord Oxmantown.

The spectrum consists of the two brighter of the lines usually present. A continuous spectrum is doubtful. Once or twice a very faint continuous spectrum was suspected.—June 1866.]

OBSERVATIONS OF NEBULÆ THE SPECTRA OF WHICH ARE APPARENTLY CONTINUOUS

[No. 105. 44 h. 18 H. V. R.A. $0^h 32^m 45^s \cdot 4$. N.P.D. $49^\circ 4' 49'' \cdot 8$. Very bright ; very gradually very much brighter in the middle.]

"Very large, much extended. Sharp nucleus, round which for some distance the nebula is bright, and then suddenly decreases ; spirality suspected."—Lord Rosse.‡

"Small stars seen on one occasion in the nucleus."—Lord Oxmantown.

Spectrum continuous.

[No. 307. 117 h. 151 H. I. R.A. $1^h 17^m 26^s \cdot 8$. N.P.D. $81^\circ 11' 50'' \cdot 3$. Very bright ; much brighter in the middle.]

Spectrum continuous.

* *Phil. Trans.*, 1833, p. 402, also Plate X. fig. 32.

† *Ibid.*, 1850, p. 513, and Plate XXXVII. fig. 2.

‡ *Ibid.*, 1861, p. 709.

[No. 575. 242 h. 156 H. I. R.A. $2^h 31^m 38^s$. N.P.D. $51^\circ 32' 45''$. Very bright; very large; very much extended; very much brighter in the middle.*]

"Six stars seen in it distinctly, others suspected about centre. Nucleus suspected to be composed of stars."—Lord Oxmantown.

Centre of the nebula very bright. The spectrum of this bright central part alone was satisfactorily seen. This spectrum is continuous.

[No. 1949. 649 h. 81 M. R.A. $9^h 43^m 48^s$. N.P.D. $20^\circ 16' 10''$. Extremely bright; extremely large; gradually, suddenly very much brighter in the middle.]

Spectrum continuous; the red end of the spectrum wanting or very faint.

[No. 1950. 82 M. R.A. $9^h 43^m 52^s$. N.P.D. $19^\circ 34' 16''$. Very bright; very large; very much extended, "a beautiful ray."]

Spectrum continuous. The absence or great faintness of the red portion of the spectrum more marked than in the spectrum of No. 1949.

[No. 3572. 1622 h. 51 M. R.A. $13^h 23^m 55^s$. N.P.D. $42^\circ 5' 4''$. Remarkable; nucleus and ring (h); spiral (R).]

"The outer nucleus unquestionably spiral with a twist to the left."—Lord Rosse.†

"Both nuclei resolved; brighter parts of spiral branches suspected to be resolved. Stars innumerable, though I feel satisfied that it is not a cluster."—Lord Oxmantown.

"Nos observations n'accusent aucun changement dans la position relative des deux têtes dans l'intervalle de 13 ans."—O. Struve.‡

Each of the bright centres brought successively upon the slit. Spectrum continuous. A suspicion that some parts of the spectrum were abnormally bright relatively to the other parts.

[No. 2841. 1175 h. 43 H. V. R.A. $12^h 12^m 1^s$. N.P.D. $41^\circ 55' 40''$. Very bright; very large; suddenly brighter in the middle; bright nucleus.]

"A very large bright extended nebula; much mottled."—Lord Rosse.§

Spectrum continuous. A suspicion of unusual brightness about the middle part of the spectrum.

[No. 3474. 1570 h. 63 M. R.A. $13^h 9^m 31^s$. N.P.D. $47^\circ 13' 45''$. Very bright; large; very suddenly much brighter in the middle; bright nucleus.]

"Spiral? darkness south following nucleus."—Lord Rosse.||

Spectrum continuous.

[No. 3636. 1663 h. 3 M. R.A. $13^h 35^m 40^s$. N.P.D. $60^\circ 55' 6''$. Cluster; extremely bright.]

* See also drawing by Lord Rosse, *Phil. Trans.*, 1861, Plate XXX. fig. 5.

† *Phil. Trans.*, 1861, p. 728; also *Ibid.*, 1850, Plate XXXV. fig. 1.

‡ "Bulletin de l'Académie Imp. des Sciences de St. Pétersbourg," tom. vii. p. 361.

§ *Phil. Trans.*, 1861, p. 725.

|| *Ibid.*, p. 729.

"Ein leicht auflöslicher Hauf zahllosen Sterne, in der Mitte zu einem einzigen Lichte von grosser Helligkeit zusammenlaufend."—D'Arrest.*

Spectrum continuous.

[No. 4058. 1909 h. 215 H. I. R.A. $15^h 2^m 36^s.3$. N.P.D. $33^\circ 41' 39''$. Very bright; considerably large; gradually brighter in the middle.]

"None of the component stars to be seen. Resolvability strongest near nucleus."—Lord Oxmantown.

Spectrum continuous.

[No. 4159. 1945 h. R.A. $15^h 58^m 49^s.9$. N.P.D. $81^\circ 31' 23''$. Star 7th mag. in photosphere.]

No unusual appearance was detected in the continuous spectrum of the star.

[No. 4230. 1968 h. 13 M. R.A. $16^h 36^m 41^s.2$. N.P.D. $53^\circ 16' 19''$. Cluster; extremely bright.]

Spectrum of the central blaze continuous. Spectrum ends abruptly in the orange. The light of the brighter part is not uniform; probably it is crossed either by bright lines or by lines of absorption.

[No. 4238. 1971 h. 12 M. R.A. $16^h 39^m 58^s.1$. N.P.D. $91^\circ 41' 47''$. Cluster; very bright.]

"Hairy branches with slightly spiral arrangement."—Lord Oxmantown.

Spectrum continuous.

[No. 4244. 50 H. IV. R.A. $16^h 43^m 6^s.4$. N.P.D. $42^\circ 8' 38''$. Very bright; large; round; disk + faint, barely resolvable, border.]

"Eine kleine Nebelscheibe, hell = $\ast 9$ Gr., umgeben von einer merklich schwächeren Nebelhülle; kreisrund 1' diam. Ruhiges Licht, bläulich."—D'Arrest.†

Spectrum continuous. No appearance of bright lines when the slit was made narrow.

[No. 4256. 10 M. R.A. $16^h 49^m 47^s.6$. N.P.D. $93^\circ 52' 6''$. Cluster; bright; well resolved.]

"The most important stars take a spiral arrangement."—Lord Oxmantown.

Spectrum continuous.

[No. 4315. 14 M. R.A. $17^h 30^m 16^s$. N.P.D. $93^\circ 9' 25''$. Cluster; bright; well resolved.]

Spectrum continuous.

[No. 4357. 3719 h. 199 H. II. R.A. $17^h 54^m 13^s.9$. N.P.D. $98^\circ 56' 37''$. Pretty bright; pretty large; round; partially resolved.]

Spectrum of the central, brighter part of the nebula continuous. As far as the light permitted, the marginal portion of the nebula was also examined, and appeared to give a continuous spectrum.

[No. 4437. 2019 h. 11 M. R.A. $18^h 43^m 37^s.2$. N.P.D. $96^\circ 26' 7''$. Cluster; very bright.]

* "Beobachtungen der Nebelflecken und Sternhaufen," p. 338.

† *Ibid.*, p. 341

"Stars curiously broken up into groups."—Lord Oxmantown.

The continuous spectra of all the brighter stars of this cluster were separately visible. When the clockwork of the equatorial was stopped, an interesting spectacle was presented by the flashing in rapid succession of the linear spectra of the minute stars of the cluster as they passed before the slit.

In no part of the cluster was any trace of bright lines detected.*

[No. 4441. 3762 h. 47 H. I. R.A. $18^h 45^m 29\text{s}.2$. N.P.D. $98^\circ 52' 8\text{s}.5$. Cluster; well resolved.]

Spectrum continuous.

[No. 4473. Auw. N. 44. R.A. $19^h 4^m 4\text{s}.8$. N.P.D. $89^\circ 11' 51''$. Pretty bright.]†

Spectrum continuous.

[No. 4485. 2036 h. 56 M. R.A. $19^h 11^m 7\text{s}.2$. N.P.D. $60^\circ 3' 41\text{s}.6$. Cluster; bright; well resolved.]

Spectrum continuous. Suspicion of unusual brightness in the middle part of the spectrum.

[No. 4586. 2081 h. R.A. $20^h 27^m 19\text{s}.8$. N.P.D. $83^\circ 3' 41\text{s}.3$. Bright cluster.]

Spectrum continuous.

[No. 4625. 2097 h. 52 H. I. R.A. $20^h 54^m 43\text{s}.8$. N.P.D. $74^\circ 21' 51\text{s}.7$. Bright; pretty large; round; gradually brighter in the middle.]

"Round. Bright middle."—Lord Rosse.‡

Spectrum continuous.

[No. 4600. 2088 h. 15 H. V. R.A. $20^h 39^m 53\text{s}$. N.P.D. $59^\circ 47' 14\text{s}.8$. Pretty bright; κ Cygni involved.]

"It is very long and winding, and runs northward from κ full 2 fields' breadth ($30''$). The nebulosity is milky, and does not seem to arise from small stars in the Milky Way ill seen."—Sir John Herschel.§

"This nebula resembles the Milky Way, and is full of dark uneven rifts or lanes. There are portions of its preceding edge clearly resolvable."—Lord Rosse.||

I was not able to obtain a satisfactory spectrum of the nebula. The spectrum of the involved star was carefully examined. No peculiarity was observed in the continuous spectrum of the star. I have, however, the impres-

* This absence of any indication of gaseous matter is in accordance with telescopic observation. D'Arrest remarks of this cluster, "Mit Verg. 11 zerfällt der Sternhauf in deutlich gesonderte Gruppen mit leeren Zwischenräumen."—"Beobachtungen der Nebelflecken und Sternhaufen," p. 346.

Lord Rosse observes: "In such objects as clusters we find no new feature; nothing which had not been seen with instruments of inferior power."—*Phil. Trans.*, 1844, p. 322.

† "This is the nebula discovered by Mr. Hind on March 30, 1845. It was observed in May 1852 as a nebula of the first class; subsequently as 'pretty faint and diluted.' M. Auwers found it 'surprisingly faint,' and of the second class at the highest."—*Phil. Trans.*, 1864, p. 38.

‡ *Phil. Trans.*, 1861, p. 734.

§ *Ibid.*, 1833, p. 468.

|| *Ibid.*, 1861, p. 733.

sion that the spectrum of the star, from about F towards the more refrangible end, appeared bright relatively to the other part. This might arise from groups of dark lines in the less refrangible portion of the spectrum.

[No. 4760. 2149 h. 207 H. II. R.A. $22^h 1^m 37^s.4$. N.P.D. $59^\circ 20' 35''$. Bright; extremely resolvable.]

"There is no doubt this nebula is a cluster."—Lord Oxmantown.

Spectrum continuous.

[No. 4815. 2172 h. 53 H. I. R.A. $22^h 30^m 39^s.5$. N.P.D. $56^\circ 20' 5''$. Bright; pretty large; suddenly much brighter in the middle.] *

"Stars sparkling near centre."—Lord Oxmantown.

Spectrum continuous.

[No. 4821. 2173 h. 233 H. II. R.A. $22^h 30^m 44^s$. N.P.D. $66^\circ 55' 34''$. Considerably bright; small; very suddenly much brighter in the middle, star 11th mag.]

Spectrum continuous.

[No. 4879. 2199 h. 251 H. II. R.A. $22^h 53^m 8^s$. N.P.D. $74^\circ 46' 10''$. Pretty bright; very gradually brighter in the middle.]

Spectrum continuous.

[No. 4883. 2201 h. 212 H. II. R.A. $22^h 54^m 17^s.6$. N.P.D. $60^\circ 36' 32''$. Considerably bright; gradually much brighter in the middle; barely resolvable.]

"Centre almost certainly resolvable."—Lord Oxmantown.

The spectrum does not consist of one or two lines only. I believe that it is continuous.

The discovery, by means of prismatic observation, that some of the nebulae are gaseous in constitution, invests these objects with a new importance to the theories of cosmical science. A first consideration of these nebulae would suggest that we have now evidence from observation of the existence of that primordial nebulous matter required by the theories of Sir William Herschel and Laplace.† But though it should be found ultimately that, in some of its forms, the theory of the development of aërifluid matter into suns and planets is a true representation of the mode of formation of the universe, still it would show a want of the strict caution, which experimental science demands in the interpretation of observed facts, to explain the phenomena presented by the gaseous nebulae in connection with the requirements of a theory which at present is not more than a speculation. In a paper "On the Spectrum of the Great Nebula in Orion,"‡ I stated, as the result of the observations which I had

* See drawing by Lord Rosse, *Phil. Trans.*, 1861, Plate XXX. fig. 39.

† A cosmical theory, which may perhaps be described as the converse of the nebular hypothesis, has been recently suggested by Professor E. W. Brayley: see *Proc. Roy. Soc.*, vol. xiv., p. 120.

‡ *Proc. Roy. Soc.*, vol. xiv., p. 39.

then made, the provisional opinion that the gaseous nebulæ may belong possibly to an order of cosmical bodies distinct from that represented by the sun and fixed stars. In this connection it may be remarked that my examination of the light of Comet I. 1866* shows that a close relation probably exists between nebular and cometary matter.†

As further contributions towards a future determination of the true rank and cosmical relations of these nebulæ, I proceed to give the results of some observations on the intensity of their light, and also measures of some of the planetary nebulæ.

ON A MODE OF DETERMINING THE BRIGHTNESS OF SOME OF THE NEBULÆ

As long as the nebulæ were regarded as aggregations of discrete stars separately invisible, it was not possible by any photometric estimation of the light from them which reaches the earth, to ascertain the intrinsic brilliancy of the suns of which the nebulæ were supposed to consist. For since these stars have no sensible magnitude even when separately visible, their intrinsic splendour could not be estimated from their brightness to an observer on the earth, so long as their distance from our system remained unknown.

Now, however, that the application of prismatic analysis to the light of the nebulæ has shown that some of these objects consist of luminous gas existing in masses which are probably continuous, though, indeed, in some cases, this aëriform matter appears to be aggregated into portions of unequal brilliancy, the intrinsic brightness of these nebulæ may be estimated from the earth, though their distance from us is unknown. The nebulæ are not points without sensible magnitude in the telescope, but present surfaces, in some cases, subtending a considerable angle. The brilliancy of a luminous surface, when beyond the earth's atmosphere, does not vary with its distance from the observer, except as it may be diminished by a possible power of extinction belonging to celestial space. For the diminution of brightness of a luminous surface, as it becomes more distant, takes place in the same proportion as the surface decreases in apparent magnitude; as long, therefore, as a distant object remains of sensible size in the telescope, the object retains its original brightness unaltered. If, therefore, the light of these nebulæ be compared with a luminous body on the earth, we can obtain approximately the intrinsic intensity of their light in terms expressing a proportion to the terrestrial light selected for comparison. The values of the intrinsic brilliancy of the nebulæ obtained in this way must be smaller than the true amount, because they are measures of the light after it has traversed an unknown extent of celestial space, and has passed through the earth's atmosphere. The amount by which, from these

* *Proc. Roy. Soc.*, vol. xv., p. 5. † My later observations were not in favour of this view.

causes, the estimated brightness of the nebulae would be too small must remain for the present unknown, since we have no data by which this loss could be even estimated.*

Notwithstanding these errors of unknown amount with which the results of a comparison of the nebulae with a terrestrial source of light must stand affected, an attempt to discover, even approximately, the intrinsic brightness of the gaseous nebulae has some importance in connection with the physical constitution which prismatic analysis has shown these objects to possess. The coincidence of two of the three lines forming the spectra of some of the nebulae, severally with a line of hydrogen and the brightest line of nitrogen,† appears to indicate that they consist of aërisome matter. Highly transparent bodies, such as these gases are, emit when heated but a feeble light compared with that which would be radiated, at the same temperature, by more opaque bodies. The invisibility of these nebulae to the naked eye, though some of them are of considerable apparent size, shows that they possess a very feeble degree of luminosity.‡

Besides these considerations, by means of similar photometric observations made at considerable intervals of time, it would be possible to ascertain whether the intrinsic brightness of the gaseous nebulae is undergoing increase or diminution, or is subject to a periodic variation.

For the purpose of making these observations I had constructed, by Mr. G. Dollond, an instrument in which are combined two forms of apparatus contrived by the Rev. W. R. Dawes, F.R.S., and described by him under

* In 1744 Chésaux was led by theoretical speculations to assume that light is gradually extinguished in its passage through space. By somewhat similar reasoning Olbers (in 1823) assumed that a star loses the $\frac{1}{800}$ of its intensity in traversing a distance of space equal to that which separates Sirius from the sun—"Über die Durchsichtigkeit des Weltraums," Bode's *Jahrbuch*, 1826, S. 110-121.

The elder Struve, from an examination of Sir W. Herschel's telescopic gauges of the Milky Way, supposed that a star of the sixth magnitude has lost $\frac{7}{100}$ of its original intensity, a star of the ninth magnitude $\frac{29}{100}$, and the smallest star visible in Sir William Herschel's telescope $\frac{88}{100}$.—“*Études d'Astronomie stellaire*,” p. 89.

A fundamental element of the reasoning by which Struve obtained these values was, that the stars are distant from our system in the inverse ratio of their apparent brightness. Since, however, the stars to which observation assigns the largest parallax, 61 Cygni and α Centauri, are less bright than other stars in which no parallax, or a much smaller one only, has been detected (not to refer to what may be regarded as an exceptional case, the great inequality in magnitude of some binary stars), this assumption that the apparent brightness of stars depends alone upon their distance, has been shown not to be true in the cases in which it has been confronted with observation.

(Recent photographic work seems to point to a diminution of light in space acting more strongly on the more refrangible rays, which may be due to an absorption, or to a scattering from fine particles, or to both. The light measured, in the case of nebula 4628, was at $\lambda 5007$ and $\lambda 4959$, and in the case of the other two at $\lambda 5007$; about the middle of the visible spectrum [1909].)

† For final positions of the nebular lines, see pp. 186 and 189.

‡ “It is evident that the intrinsic splendour of their surfaces, if continuous, must be almost infinitely less than that of the sun.”—Sir John Herschel, “Outlines of Astronomy,” p. 646, 7th ed.

the names of "an aperture-diminishing eyepiece" and "a photometer of neutral-tint glass." *

This instrument, which is adapted to the eye-end of my achromatic telescope, consists essentially, first, of a diaphragm drilled with small holes movable within the focus of the telescope, which diminishes the aperture of the telescope in proportion as it is advanced towards the object-glass; and secondly, of two graduated wedges of neutral-tint glass, which slide in front of the convex lenses with which the focal image is viewed. The aperture in the diaphragm which was used in the following observations has a diameter of 0·06 inch. The diaphragm is moved by a screw, and its position is read off upon a scale divided into tenths of an inch. The photometer wedges are 4 inches in length and divided into forty parts.

The observations were made in the following way:—

The diaphragm was placed so that all the pencils from the object-glass passed through the small aperture without diminution. The nebulae were viewed through the wedges of neutral-tint glass. These were made to slide before the eye, until the exact part of one of the wedges was found, at which the nebula was extinguished.

On August 25, 1865, a night of more than usual clearness, several estimations were made of each of the three nebulae, No. 4628, 1 H. IV., the annular nebula in Lyra, and the Dumb-bell nebula. In each case the estimation applies to the brightest part of the nebula.

The source of light selected as a standard of comparison was a sperm candle of the size known as "six to the pound."

The rate of burning this candle on three occasions was—

August 26	35 minutes lost in weight	132 grs. = 157·8 grs. per hour.
" 31	38 "	142 grs. = 160·8 grs. "
September 7	41 "	148 grs. = 157·8 grs. "

It was found necessary to diminish greatly the light of the candle in order to bring it within the range of comparison afforded by the movable diaphragm.

For this purpose a thick plate, with parallel sides, of neutral-tint glass was placed before the flame of the candle. An examination of the neutral-tint glass with a prism showed that the absorptive power of the glass for all infrangibilities in the brighter portions of the spectrum was very nearly uniform. The amount of diminution of the light of the candle effected by the plate of neutral glass was measured by a Bunsen's photometer. When the light passed through the neutral glass, the candle required to be placed at a distance of 6·5 inches to cause the ungreased central spot of the photometer to disappear. Without the glass, the disappearance took place when the

* *Monthly Notices R.A.S.*, vol. xxv., p. 229.

candle was removed to a distance of 126·25 inches. The disappearance was viewed with a small telescope. The numbers adopted are the mean of several observations, the close accordance of which showed that the fixed light behind the screen had remained of constant intensity. The ratio of the squares of the distances shows that the light of the candle was reduced by the neutral-tint glass to the $\frac{1}{377}$ part of its original intensity.

The candle, placed in a lantern and screened by the neutral-tint glass, was fixed on the roof of a house at a distance of 440 yards from the observatory.* It was desirable that the candle should be at some distance, in order that its image in the telescope should be formed at nearly the same distance from the object-glass as the images of celestial objects. Besides, it was convenient that the flame of the candle should appear small, when viewed with the convex lens, magnifying on the telescope 101 diameters, with which the nebulae had been observed.

The image of the flame of the candle in the telescope was viewed through the same parts of the wedges of neutral-tint glass at which the nebulae had been observed to become invisible. By means of the movable diaphragms, and also independently by means of diaphragms placed before the object-glass, the apertures of the object-glass were found at which the flame of the candle became extinguished at the parts of the wedges at which the nebulae had been observed to disappear.

	Sept. 7, 1865.	Jan. 19, 1866.
Aperture corresponding to nebula in Lyra	2·09 inches.	2·00 inches.
" " Dumb-bell nebula	1·06 inch.	1·20 inch.
" " Nebula No. 4628. 1 H. IV.	4·0 inches.	

Taking into consideration the circumstances of the observations, I adopt for the

Dumb-bell nebula	an aperture of 1·10 inch.
Annular nebula in Lyra	" " 2·00 inches.
Nebula No. 4628	" " 4·00 inches.

The disappearance of the nebulae with the neutral-tint glass wedges had been observed with the full aperture of the telescope (8 inches), therefore the ratios of the areas of the aperture corresponding to the diameters of 1·10 inch, 2·00 inches, and 4·00 inches, to the area of the full aperture of the telescope, will give the intensities of the nebulae in terms of the candle screened with the neutral-tint glass. The results are—

$$\begin{aligned} \text{Dumb-bell nebula} & = \frac{1}{52} \\ \text{Nebula in Lyra} & = \frac{1}{16} \\ \text{Nebula No. 4628} & = \frac{1}{4} \end{aligned}$$

of the intensity of the obscured candle.

* I gratefully acknowledge the assistance of my friend, Mr. S. B. Kincaid, F.R.A.S., who took the management of the candle.

The neutral-tint glass reduces the intensity of the candle to the $\frac{1}{377}$ part, therefore the intensities of the nebulæ in terms of the intensity of the unscreened flame of the sperm candle are—

$$\begin{aligned} \text{Nebula No. 4628} & = \frac{1}{1508}, \\ \text{Annular nebula in Lyra} & = \frac{1}{8632}, \\ \text{Dumb-bell nebula} & = \frac{1}{19604}. \end{aligned}$$

It may be remarked, in connection with these values of the intensity of the light of these nebulæ, that nebula No. 4628 gives a spectrum of three bright lines, and also a faint continuous spectrum. The nebula in Lyra and the Dumb-bell nebula give one bright line only.

MEASURES OF SOME OF THE NEBULÆ

If great physical changes, such as subsidence and condensation, of the magnitude necessary for the conversion of the nebulæ into suns are taking place in these objects, an indication of the advance of these processes might perhaps be obtained by measurements, taken at considerable intervals, of such of the nebulæ as are suitable for this purpose. There are several of the planetary nebulæ which give a gaseous spectrum, which in telescopes of moderate power have disks sufficiently well defined for micrometric measurement. Measures of these nebulæ would be comparable with future measures obtained with telescopes of similar power.

Some months since I invited the Rev. W. R. Dawes, F.R.S., to take measures of the diameters of several of these objects. Ill-health has unfortunately prevented him from measuring more than one nebula, No. 4234, 5Σ . Mr. Dawes writes: "So bright and yet so imperfectly defined, like the heads of some comets. The moon was near the horizon, yet I found that I could get hold of more of it with high powers than with lower. It appeared rather suddenly to fade away at the edges, and to have a sort of faint halo round it, which, however, was not distinctly separate from the brighter centre. I obtained four sets of measures of the diameter which was parallel to the equator; but thought that the form was rather elliptic, the equatorial diameter being the greater. The four sets were obtained with powers 148, 218, 292, and 382; that with 148 appearing to be far less certain than the others. The illumination of the field necessary to show the wires with power 148 seemed to diminish the visibility of the nebula more than did the increase of power; with which the wires were sufficiently seen with much less illumination. The results were:

$$\begin{array}{l} \text{With power 148 diam.} = 14\cdot23 \\ \text{"} 218 \text{ } " = 15\cdot76 \\ \text{"} 292 \text{ } " = 15\cdot70 \\ \text{"} 382 \text{ } " = 16\cdot23 \end{array} \left. \right\} \text{Mean of all } 15\cdot5.$$

"Mean of the three higher powers = $15''\cdot 9$, which I consider worthy of much more confidence. I could not see the fainter halo sufficiently well with any illumination to get safe measures of it. These results refer to the brighter disk only."

Measures of this nebula by former observers :

1833,	diam.	=	$8''$	Sir John Herschel.*
1856, March,	"	=	$6''$	D' Arrest } [†]
1856, June,	"	=	$8''$	D' Arrest } [†]
1864, August,	"	=	$9\cdot 6''$	Schultz } [‡]
			= $14\cdot 5''$	Auwers? } [‡]

Nebula No. 4514. 2050 h. 73 H. IV. I made careful measures of this object on two occasions. Wire micrometer with dark ground illumination.

1865. Nov. 25. Power 333. Mean of six measures $31''\cdot 06$.

1865. Dec. 15. Power 680. Mean of three measures $30''\cdot 66$.

I think the measures of December 15 are entitled to more confidence than those of November 25. I should prefer to take as the most probable value—Diam. in R.A. = $30''\cdot 8$.

1833. Diam. in R.A. = $45''\cdot 5$. Sir John Herschel. §

1864. Diam. in R.A. = $0'\cdot 4$. Schultz. ||

FURTHER OBSERVATIONS ON THE SPECTRA OF THE NEBULÆ

(From *Phil. Trans.*, vol. clviii., p. 540, 1868)

OBSERVATIONS OF NEBULÆ

FOR the greater convenience of reference and of comparison, the spectrum of 37 H. IV. Draconis, from my paper "On the Spectra of some of the Nebulæ," ¶ has been added. (See fig. 17, p. 110.) The spectrum of this nebula may be taken as characteristic, in its general features, of the spectra of all the nebulae which do not give a continuous spectrum. At present I have determined satisfactorily the general characters of the spectra of about seventy nebulae. This number forms but a part of the much larger list of nebulae which I have examined, but in the case of many of these objects their light was found to be too feeble for a satisfactory analysis. Of these seventy nebulae about one-third give a spectrum of bright lines. The proportion, which is indicated by this examination, of the nebulae which give a spectrum of bright lines to those

* *Phil. Trans.*, 1833, p. 458.

† "Beobachtungen der Nebelflecken und Sternhaufen," p. 341.

‡ *Astronom. Nachrichten*, No. 1541, p. 70.

§ *Phil. Trans.*, 1833, p. 464.

|| *Astronom. Nachrichten*, No. 1541.

¶ *Phil. Trans.*, 1864, p. 438.

of which the spectrum is continuous (namely, as one to two), is probably higher than would result from a wider observation of the objects contained in such catalogues as those of Sir John Herschel and Dr. D'Arrest, since many of the objects which I examined were specially selected, on account of the probability (which was suggested by their form or colour) that they were gaseous in constitution.

All the differences which I have hitherto observed between the spectra of the gaseous nebulæ may be regarded as modifications only of the typical form of spectrum which is represented in the diagram, since they consist of differences of relative intensity, of the deficiency of one or two lines, or of the presence of one or two additional lines. It is worthy of remark that, so far as the nebulæ have been examined, the brightest of the three lines, which agrees in position in the spectrum with the brightest of the lines of the spectrum of nitrogen,* is present in *all* the nebulæ which give a spectrum indicative of gaseity. It is a suggestive fact, that should not be overlooked, that in no nebula which has a spectrum of bright lines has any additional line† been observed on the less refrangible and brighter side of the line common to all the gaseous nebulæ.

The faint continuous spectrum, which in some cases is also seen, has been traced in certain nebulæ, by its breadth, to a distinct brighter portion of the nebula which it is convenient still to distinguish by the term "nucleus," though at present we know nothing of the true relation of the bright points of the nebulæ to the more diffused surrounding portions.

It must not be forgotten that when gases are rendered luminous there may usually be detected a faintly luminous continuous spectrum. In the case of several of the nebulæ, such as the annular nebula of Lyra and the Dumb-bell nebula, no existence of even a faint continuous spectrum has been yet certainly detected.

The determination of the position in the spectrum of the three bright lines was obtained by simultaneous comparison with the lines of hydrogen, nitrogen, and barium. The instrument which I employed had two prisms, each with a refracting angle of 60° , and the positions of the lines were trustworthy within the limits of about the breadth of the double line D.

The objects which I proposed to myself, in attempting a re-examination of some of the nebulæ with the large instrument described in this paper, were to determine, first, whether any of the nebulæ were possessed of a motion which could be detected by a change of refrangibility; secondly, whether the coincidence which had been observed of the first and the third line with a line of hydrogen

* See later observations of the position of this line, p. 186.

† A line bright enough to be seen by eye. At a later date C, D₃, and a line at 5400 were observed by Keeler and Campbell. (1909.)

and a line of nitrogen would be found to hold good when subjected to the test of a spreading out of the spectrum three or four times greater than that under which the former observations were made. It would not, it seemed, be difficult, in the case of the detection of a want of coincidence, to separate the effects of the two distinct sources referred to, from both of which equally a minute difference of refrangibility between the nebular lines and those of terrestrial substances might arise. The probability is very great indeed that in all the nebulae which give the kind of spectrum of which I am speaking, the two lines referred to are to be attributed to the same two substances, and that therefore, in all these nebulae, they were originally of the same degree of refrangibility. On the other hand, it is not to be supposed that nebulae situated in different positions in the heavens would have a similar motion relatively to the earth. An examination of several nebulae would therefore show to which of these causes any observed want of coincidence was to be attributed.

The Great Nebula in Orion.—In my description of this nebula* I stated that the light from all the parts of the strangely diversified object, which were bright enough to be observed with my instrument, was resolved into three bright lines similar to those represented in the diagram.

On the present occasion I applied myself in the first place to as careful a comparison as possible of the brightest line with the corresponding line of the spectrum of nitrogen.

My first observations were made with the light from the induction-spark taken in pure nitrogen sealed in a tube at a tension a little less than that of the atmosphere, which was reflected into the instrument, as in my former series of observations, by means of a mirror and a small prism. The precaution was taken to verify the accuracy of the position of the spectrum of comparison relatively to that of the nebula, by placing a small lamp before the object-glass in the way already described.

The coincidence of the line in the nebula with the brightest of the lines of nitrogen, though now subjected to a much more severe trial, appeared as perfect as it did in my former observations. I expected that I might discover a duplicity in the line in the nebula corresponding to the two component lines of the line of nitrogen, but I was not able, after long and careful scrutiny, to see the line double. The line in the nebula was narrower than the double line of nitrogen; this latter may have appeared broader in consequence of irradiation, as it was much brighter than the line in the nebula.

The following observations are suggestive in connection with the point under consideration. Electrodes of platinum were placed before the object-glass in the direction of a diameter, so that the spark was as nearly as possible

* *Proc. Roy. Soc.*, vol. xiv., p. 39.

before the centre of the lens. The spark was taken in air. I expected to find the spectrum faint, for the reasons which have been stated in a previous paragraph, but I was surprised to find that only one line was visible in the large spectroscope when adapted to the eye-end of the telescope. This line was the one which agrees in position with the line in the nebula, so that under these circumstances the spectrum of nitrogen appeared precisely similar to the spectra of those nebulæ of which the light is apparently monochromatic. This resemblance was made more complete by the faintness of the line; from which cause it appeared much narrower, and the separate existence of its two components could no longer be detected. When this line was observed simultaneously with that in the nebula, it was found to appear but a very little broader than that line. When the battery circuit was completed, the line from the spark coincided so accurately in position with the nebular line, that the effect to the eye was as if a sudden increase of brightness in the line of the nebula had taken place. In order to make this observation, and to compare the relative appearance of the lines, the telescope was moved so that the light from the nebula occupied the lower half only of the slit. The line of the spark was now seen to be a very little broader than the line of the nebula, and appeared as a continuation of it in an unbroken straight line. These observations were repeated many times on several nights.

An apparent want of coincidence, which would be represented by 0·02 division of the head of the micrometer-screw, would be about the smallest difference that could be observed under the circumstances under which these observations were made. At the part of the spectrum where this line of nitrogen occurs, the angular interval measured by 0·02 division of the micrometer corresponds to a difference of wave-length of 0·0460 millionth of a millimetre.

At the time the comparisons were made the earth was receding from the part of the heavens in which the nebula is situated by about half its orbital velocity. If the velocity of light be taken at 185,000 miles per second, and the wave-length of the nitrogen line at 500·80 millionths of a millimetre, the effect of half the orbital motion would be to degrade the refrangibility of the line by 0·023, an alteration of wave-length which would correspond to about 0·01 of the large micrometer-head, an interval too small to be detected.

We learn from these observations, that if the line be emitted by nitrogen, the nebula is not receding from us with a velocity greater than ten miles per second; for this motion, added to that of the earth's orbital velocity, would have caused a want of coincidence that could be observed. Further, that if the nebula be approaching our system, its velocity may be as much as twenty or twenty-five miles per second; for part of its motion of approach would be masked by the effect of the motion of the earth in the contrary direction.

The double line in the nitrogen-spectrum does not consist of sharply

defined lines, but each component is nebulous, and remains of a greater width than the image of the slit.* The breadth of these lines appears to be connected with the conditions of tension and of temperature of the gas. Plücker † states that when an induction-spark of great heating power is employed, the lines expand so as to unite and form an undivided band. Even when the duplicity exists, the eye ceases to have the power to distinguish the component lines, if the intensity of the light be greatly diminished.

Though I have been unable to detect duplicity in the corresponding line in the nebula, it might possibly be found to be double if seen under more favourable conditions; I incline to the belief that it is not double.‡

In my tables of the lines of the air§ I estimated the brightness of each of the components of the double line in the spectrum of nitrogen at 10, and the components of the double line next in brightness in the orange at 7 and 5, and those of a third double line on the less refrangible side of D at 6 and 4. It was with reference to these two double lines next in apparent brilliancy that I wrote.|| in speaking of the line in the nebula, "If, however, this line were due to nitrogen, we ought to see other lines as well; for there are specially two strong double lines in the spectrum of nitrogen, one at least of which, if they existed in the light of the nebulae, would be easily visible."

As the disappearance of the whole spectrum of nitrogen, with the exception of the one double line, was unexpected, though, indeed, in accordance with my previous estimations, I examined the spectrum of nitrogen with a spectroscope furnished with one prism with a refracting angle of 60° , in which the whole of the spectrum from C to G is included in the field of view. I then moved between the eye and the little telescope of the spectroscope a wedge of neutral-tint glass corrected for refraction by an inverted similar wedge of crown glass, and which I had found to be sensibly equal in absorbing power on the different parts of the visible spectrum. As the darker part of the wedge was brought before the eye, the two groups in the orange were quite extinguished, while the lines in the green still remained of considerable brightness. The line which under these circumstances remained longest visible, next to the brightest line, was one more refrangible at 2669 of the scale of my map. This observation was made with a narrow slit. When the induction-spark was looked at from a distance of some feet with a direct-vision prism held close to the eye, I was surprised to observe that the double line in the orange appeared to me to be the brightest in the spectrum, and when the neutral-

* Secchi states that with his direct spectroscope this line in the annular nebula in Lyra appears double. As the image of the nebula is viewed directly, after elongation by the cylindrical lens, and without a slit, it is probable that the two lines may correspond to the two sides of the elongated annulus of the nebula.

† *Phil. Trans.*, 1863, p. 13.

‡ "On the Spectra of the Chemical Elements," *Phil. Trans.*, 1864, p. 141.

§ *Ibid.*

|| *Ibid.*, p. 443.

tint wedge was interposed, this line in the orange remained alone visible, all the other lines being extinguished.

When, however, in place of the simple prism a small direct-vision spectroscope provided with a slit was employed, I found it to be possible, by receding from the spark, to find a position in which the double line in the green, with which the line in the nebula coincides, was alone visible, and the spectrum of the spark in nitrogen resembled that of a monochromatic nebula.

It is obvious that if the spectrum of hydrogen were reduced in intensity, the line in the blue, which corresponds to that in the nebula, would remain visible after the line in the red and the lines more refrangible than F had become too feeble to affect the eye.

It therefore becomes a question of much interest whether the one, two, three, or four lines seen in the spectra of these nebulae represent the whole of the light emitted by these bodies, or whether these lines are the strongest lines only of their spectra, which, by reason of their greater intensity, have succeeded in reaching the earth. Since these nebulae are bodies which have a sensible diameter, and in all probability present a continuous luminous surface, or nearly so, we cannot suppose that any lines have been extinguished by the effect of the distance of these objects from us.

If we had evidence that the other lines which present themselves in the spectra of nitrogen and hydrogen were quenched on their way to us, we should have to consider their disappearance as an indication of a power of extinction residing in cosmical space, similar to that which was suggested from theoretical considerations by Chézeaux, and was afterwards supported on other grounds by Olbers and the elder Struve. Further, as the lines which we see in the nebulae are precisely those which experiment shows would longest resist extinction, at least so far as respects their power of producing an impression on our visual organs, we might conclude that this absorptive property of space is not *elective* in its action on light, but is of the character of a *general* absorption acting equally, or nearly so, on light of every degree of refrangibility. Whatever may be the true state of the case, the result of this re-examination of the spectrum of this nebula appears to give increased probability to the suggestion that followed from my former observations—namely, that the substances hydrogen and nitrogen are the principal constituents of the nebulae of the class under consideration.*

I now pass to observations of the third line of the nebular spectrum, the one which I found to coincide with the line of hydrogen, which corresponds to Fraunhofer's F. The substance in the nebulae which is indicated by this line appears to be subject to much greater variation in relative brilliancy, or to be more affected by the conditions under which it emits light; for while the brightest line is always present, the line of which I am speaking seems to be wholly

* See final result, pp. 186 and 189.

wanting in some nebulae, and to be of different degrees of relative brightness in some other nebulae.

In the nebula of Orion this line is relatively stronger than in 37 H. IV. Draconis, and some other nebulae. I have suspected that the relative brightness of this line varies slightly in different parts of this nebula. It may be estimated perhaps in the nebula of Orion at about the brightness of the second line. The second line suffers in apparent brilliancy from its nearness to the brightest line, and may, without due regard to this circumstance, be estimated as brighter than the third line.

In order to compare the position of the line with that of the corresponding line in the spectrum of hydrogen, I employed a vacuum-tube containing hydrogen at a very small tension, which was placed before the object-glass of the telescope. Under these conditions the line appears narrow, when the slit is narrow, without any sensible nebulosity at the edges. The character of the line is altered, as has been shown by Plücker, when hydrogen at the atmospheric pressure is employed; the line then expands into a nebulous band of considerable width, even with a very narrow slit. Such a condition of the line is obviously unsuitable for the delicate comparisons which it was proposed to attempt.

The narrow, sharply-defined line of hydrogen, when the vacuum-tube was before the slit, was observed to coincide perfectly in position with the third line of the nebula. This observation, which shows the coincidence of these lines with an accuracy three or four times as great as my former observations, increases in the same ratio the probability that the line in the nebula is really due to luminous hydrogen.

I suspect that, although the third line in this nebula may impress the eye as strongly as the second line, yet it is not so narrow and well-defined as that line. If this suspicion be correct, this condition of the line might indicate that the hydrogen exists at a rather greater tension than that in the so-called vacuum-tubes, but that it is not nearly so dense as would correspond to the atmospheric pressure at the surface of the earth. As, however, the character of the lines of hydrogen is also greatly modified by temperature, it is not possible to reason with any certainty as to the state of things in this distant object, the light of which we have now under examination.

I am still unable to find any terrestrial line which corresponds to the middle line. I have made the additional observation that the line in the nebula is in a very slight degree less refrangible than the line of oxygen at 2060 of the scale of my map. It is in a rather larger degree less refrangible than the strong line of barium at 2075 of my scale.

Several other nebulae have been observed with the large spectroscope. I prefer, however, to re-examine these objects before I publish any observations of them.

ON THE SPECTRUM OF THE GREAT NEBULA IN ORION

(From *Proc. Roy. Soc.*, vol. xx., p. 379, 1872)

IN my early observations of the spectrum presented by the gaseous nebulæ, the spectroscope with which I determined the coincidence of two of the bright lines respectively with a line of nitrogen and a line of hydrogen was of insufficient dispersive power to show whether the brightest nebular line was double, as is the case with the corresponding line of nitrogen.

Subsequently I took some pains to determine this important point by using a spectroscope of greater dispersive power. I found, however, that the light furnished by the telescope of 8 inches aperture, to which the spectroscope was attached, was too feeble, even in the case of the brightest nebulæ, to give the line with sufficient distinctness when a narrow slit was used. The results of this later examination are given in a paper I had the honour of presenting to the Royal Society in 1868. I there say* : "I expected that I might discover a duplicity in the line in the nebula corresponding to the two component lines of the line of nitrogen, but I was not able, after long and careful scrutiny, to see the line double. The line in the nebula was narrower than the double line of nitrogen; this latter line may have appeared broader in consequence of irradiation, as it was much brighter than the line in the nebula." When the spark was placed before the object-glass of the telescope, the light was so much weakened that one line only was visible in the spectroscope. "This line was the one which agrees in position with the line in the nebula, so that under these circumstances the spectrum of nitrogen appeared precisely similar to the spectra of those nebulæ of which the light is apparently monochromatic. This resemblance was made more complete by the faintness of the line; from which cause it appeared narrower, and the separate existence of its two components could no longer be detected. When the line was observed simultaneously with that in the nebula, it was found to appear but a very little broader than that line." I also remark: "The double line in the nitrogen-spectrum does not consist of sharply defined lines, but each component is nebulous, and remains of a greater width than the image of the slit. The breadth of these lines appears to be connected with the conditions of tension and temperature of the gas. Plücker† states that when an induction-spark of great heating power is employed, the lines expand so as to unite and form an undivided band. Even when the duplicity exists, the eye ceases to have the power to distinguish the component lines, if the intensity of the light be greatly diminished." I state further: "I incline to the belief that it [the line in the nebula] is not double."

* *Phil. Trans.*, 1868, pp. 542, 543.† *Ibid.*, 1865, p. 13.

One of the first investigations which I proposed to myself when, by the kindness of the Royal Society, I had at my command a much more powerful telescope, was the determination of the true character of the bright line in the spectra of the nebulae which is apparently coincident with that of nitrogen. From various circumstances, chiefly connected with the alterations and adjustments of new instruments, I was not able to accomplish this task satisfactorily until within the last few months.

DESCRIPTION OF APPARATUS

It seems to me desirable to give a description of the spectroscopic apparatus with which the observations in this paper were made. In the former paper, to which I have already referred, I gave some reasons* to show that the ordinary method of comparison, by reflecting light into the spectroscope by means of a small prism placed before one-half of the slit, is not satisfactory for very delicate observations unless certain precautions are taken. I then describe an arrangement for this purpose, which, with one or two modifications, is adopted in the collimator constructed for use with the Royal Society's telescope. I give the description from that paper†:

"The following arrangement for admitting the light from the spark appeared to me to be free from the objections which have been referred to, and to be in all respects adapted to meet the requirements of the case. In place of the small prism, two pieces of silvered glass were securely fixed before the slit at an angle of 45° . In a direction at right angles to that of the slit, an opening of about $\frac{1}{10}$ inch was left between the pieces of glass for the passage of the pencils from the object-glass. By means of this arrangement the spectrum of a star is seen accompanied by two spectra of comparison, one appearing above and the other below it. As the reflecting surfaces are about 0.5 inch from the slit, and the rays from the spark are divergent, the light reflected from the pieces of glass will have encroached upon the pencils from the object-glass by the time they reach the slit, and the upper and lower spectra of comparison will appear to overlap to a small extent the spectrum formed by the light from the object-glass. This condition of things is of great assistance to the eye in forming a judgment as to the absolute coincidence or otherwise of lines. For the purpose of avoiding some inconveniences which would arise from glass of the ordinary thickness, pieces of the thin glass used for the covers of microscopic objects were carefully selected, and these were silvered by floating them upon the surface of a silvering solution. In order to ensure that the induction-spark should always preserve the same position relatively to the mirror, a piece of sheet gutta-percha was fixed above the silvered glass;

* *Phil. Trans.*, 1868, pp. 537, 538.

† *Ibid.*, 1868, p. 538.

in the plate of gutta-percha, at the proper place, a small hole was made of about $\frac{1}{20}$ inch in diameter. The ebonite clamp containing the electrodes is so fixed as to permit the point of separation of these to be adjusted exactly over the small hole in the gutta-percha. The adjustment of the parts of the apparatus was made by closing the end of the adapting-tube, by which the apparatus is attached to the telescope, with a diaphragm with a small central hole, before which a spirit-lamp was placed. When the lines from the induction-spark, in the two spectra of comparison, were seen to overlap exactly, for a short distance, the lines of sodium from the light of the lamp, the adjustment was considered perfect. The accuracy of adjustment has been confirmed by the exact coincidence of the three lines of magnesium with the component lines of δ in the spectrum of the moon."

The modifications of this plan consist in the substitution of a thin silver plate polished on both surfaces for the pieces of silvered glass. The opposite side of the silver plate to that from which the terrestrial light is reflected to the slit reflects the images formed by the object-glass to the side of the tube where a suitable eyepiece is fixed. This arrangement forms a very convenient finder, for it is easy to cause the image of the star to disappear in the hole in the silver plate. When this is the case, the line of light formed by the star falls on the slit, and its spectrum is visible in the spectroscope. This collimator is so constructed that, by means of a coupling-screw, any one of three spectrosopes can be conveniently attached to it.

This apparatus performs admirably; but it seemed to me desirable, for observations of great delicacy, to be able to dispense with reflection, and to place the source of the light for comparison directly before the slit. Formerly I accomplished this object by placing the spark or vacuum-tube before the object-glass of the telescope. The great length of the present telescope renders this method inconvenient; but a more important objection arises from the great diminution of the light when the spark is removed to a distance of 15 feet from the slit. I therefore resolved to place the spark or vacuum-tube within the telescope at a moderate distance from the slit. For this purpose holes were drilled in the tube opposite to each other, at a distance of 2 feet 6 inches within the principal focus. Before these holes short tubes were fixed with screws; in these tubes slide suitable holders for carrying electrodes or vacuum-tubes. The spark is thus brought at once nearly into the axis of the telescope. The final adjustment is made in the following manner: A bright star is brought into the centre of the field of an ordinary eyepiece; the eyepiece is then pushed within the focus, when the wires or vacuum-tube can be seen across the circle of light formed by the star out of focus. The place of discharge between the electrodes, or the middle of the capillary part of the vacuum-tube, is then brought into the centre of the circle of light. The

vacuum-tubes are covered with black paper, with the exception of a space about a quarter of an inch long in the middle of the capillary part; through this small uncovered space the light passes to reach the slit.

The accuracy of both methods of comparison, that by reflection and that by the spark within the tube, was tested by the comparison of the three bright lines of magnesium and the double line of sodium with the Fraunhofer lines *b* and *D* in the spectrum of the moon. I greatly prefer the latter method, because it is free from several delicate adjustments which are necessary when the light is reflected and which are liable to be accidentally displaced.

Spectroscope A is furnished with a single prism of dense glass with a refracting angle of $59^{\circ} 42'$, giving $5^{\circ} 6'$ from A to H.

Spectroscope B has two compound prisms of Mr. Grubb's construction, which move automatically to positions of minimum deviation for the different parts of the spectrum. Each prism gives about $9^{\circ} 6'$ for minimum deviation from A to H.

Spectroscope C is furnished with four similar prisms.

The small telescopes of the three spectroscopes are of the same size: diameter of object-glass $1\frac{1}{4}$ inch; each is furnished with three eyepieces magnifying 5·5, 9·2, and 16·0 diameters.

SPECTRUM OF THE NEBULA OF ORION

With spectrosopes A and B four* lines are seen; they are represented in the diagram which accompanies this note. The scale in the diagram gives wave-lengths.

First line.—With spectroscope B and eyepiece 1 and 2, the slit being made very narrow, this line was seen to be very narrow, of a width corresponding to the slit, and defined at both edges, and undoubtedly not double. The line of nitrogen when compared with it appeared double, and each component nebulous and broader than the line of the nebula. This latter line was seen on several nights to be apparently coincident with the middle of the less refrangible line of the double line of nitrogen. This observation was on one night confirmed by observation with the more powerful spectroscope C.

The question suggests itself whether, under any conditions of pressure and temperature, the double line of the nitrogen-spectrum becomes single; and further, if this should be found to be the case, whether the line becomes single by the fading out of its more refrangible component, or in what other way the single line of the nebula comes to occupy the position in the spectrum, not of the middle of the double line of nitrogen, but that of the less refrangible of the lines.

* The fourth line was first seen in nebula 18 H. IV. (*Phil. Trans.*, 1864, p. 441).

I stated in my former paper that when for any reason the light from the luminous nitrogen is greatly reduced in intensity, the double line under consideration is the last to disappear, and consequently a state of things may be found in which the light of nitrogen is sensibly monochromatic when examined with a narrow slit.* Under these circumstances the line of nitrogen appears narrower, and the separate components can be detected with difficulty, if at all.

I stated also that the breadth of the component lines appears to be connected with the conditions of density and temperature of the gas. As was to be expected from theoretical considerations, the lines become narrower and less nebulous as the pressure is diminished. My observations of this change seemed to show that the diminution of the breadth of the lines takes place chiefly at the outer sides of the lines; so that in the light from very rarified gas the double line is narrower, but the space of separation between the components is not as much wider as would be the case if the lines had decreased equally in width on the sides towards each other.

When the pressure of the gas is reduced to about 15 inches of mercury, the line-spectrum fades out to give place to Plücker's spectrum of the first order. During this process a state of things occurs when, for reasons already stated, the spectrum becomes *sensibly* monochromatic when viewed with a narrow slit and a spectroscope of several prisms. The line is narrower, but remains double, and has the characters described in the preceding paragraph.

As the pressure is diminished, the double line fades out entirely, and the spectrum of the second order gives place to the spectrum of the first order. When, however, the pressure becomes exceedingly small, from 0·1 inch to 0·05 inch, or less, of mercury, there is a condition of the discharge in which the line again appears, while the other lines remain very faint. Under these conditions I have always been able, though with some difficulty, on account of the faint light when the necessary dispersive power (spectroscope B with second or third eyepiece) and a narrow slit are used, to see the line to be double, but it is narrower than when the gas is more dense, and may be easily mistaken for a single line. I have not yet been able to find a condition of luminous nitrogen in which the line has the same characters as those presented by the line in the nebula, where it is single and of the width of the slit.

Upon the whole I am still inclined to regard the line in the nebula as probably due to nitrogen.

* *Phil. Trans.*, 1868, pp. 540-546. Observations on this point were subsequently made by Frankland and Lockyer (*Proc. Roy. Soc.*, vol. xvii., p. 453). It should be stated that the authors make no reference to this observation, though they refer to a purely hypothetical suggestion contained in the same paper.

If this should be found to be the case, and that the nebular line has originally the refrangibility of the middle of the double line of nitrogen, then we should have evidence that the nebula is moving from the earth. The amount of displacement of the nebular line from the middle of the double line of nitrogen corresponds to a velocity of 55 miles per second from the earth. At the time of observation the part of the earth's orbital motion, which was from the nebula, was 14.9 miles per second. From the remaining 40 miles per second would have to be deducted the probable motion from the nebula due to the motion of the solar system in space. This estimation of the possible motion of the nebula can be regarded as only approximate.

If the want of accordance of the line in the nebula with the middle of the double line of nitrogen be due to a recession of the nebula in the line of sight, there should be a corresponding displacement of the third line as compared with that of hydrogen. For reasons which will be found in a subsequent paragraph, I have not been able to make this comparison with the necessary accuracy.

In my former paper* I gave reasons against supposing so large a motion in the nebula; these were based on the circumstance that the nebular line falls upon the double nitrogen line, which the present observations confirm. I was not then able to use a slit sufficiently narrow to show that the nebular line is single and not coincident with the middle of the double line of nitrogen.

I am still pursuing the investigation of the parts of this inquiry which remain unsettled.

Second line.—This line was found by my former comparisons to be a little less refrangible than a strong line in the spectrum of barium. Three sets of measures give for this line a wave-length of 4957 on Ångström's scale; this would show that the line agrees nearly in position with a strong line of iron. At present I am not able to suggest to what substance this line belongs.

This line is also narrow and defined. I suspect that the brightness of this line relatively to the first line varies in different nebulae.

Third and Fourth line.—My former observations show that these lines

* *Phil. Trans.*, 1868, pp. 542, 543.

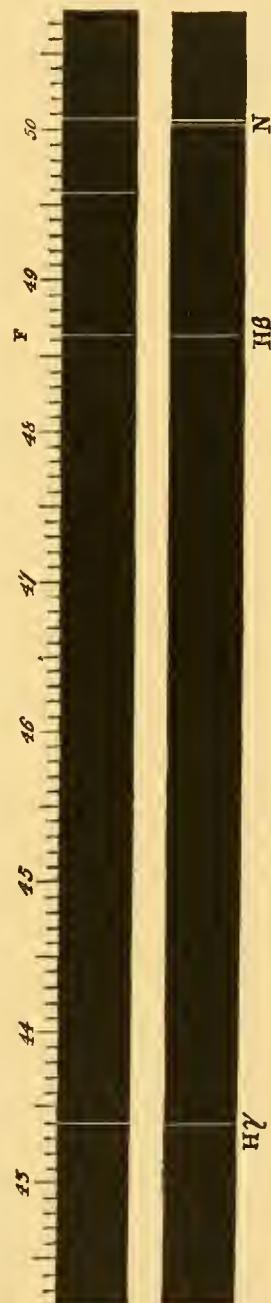


Fig. 18.

agree in position with two lines of the spectrum of hydrogen, that at F and the line near G.

These lines are very narrow and are defined; the hydrogen therefore must be at a low tension.

The brightness of these lines relatively to the first and second lines varies considerably in different nebulae; and I suspect they may also vary in the same nebulae at different times, and even in different parts of same nebula; but at present I have not sufficient evidence on these points.* I regret that, in consequence of a continuance of bad weather, I have not yet been able to obtain decisive observations as to the possible motion of the nebula in the line of sight. With spectroscope B and eyepiece 2, the lines appear to be coincident with those of hydrogen. In consequence of the uncertainty of the character of the first line, which is single, while that of nitrogen is double, this determination can now only be made by means of the comparison of the third line with that of hydrogen. This third line becomes very faint from the great loss of light unavoidable in a spectroscope that gives a sufficient dispersive power, and the comparison can only be attempted when the sky is very clear and the nebula near the meridian.

ON THE INFERENCES TO BE DRAWN FROM THE APPEARANCE OF BRIGHT LINES IN THE SPECTRA OF IRRESOLVABLE NEBULÆ

(From *Proc. Roy. Soc.*, vol. xxvi., p. 179, 1877)

In a paper recently read before the Royal Society, Mr. Stone attempts to show that the fact that the spectra of some of the irresolvable nebulae consist mainly of bright lines does not warrant the inference that these bodies are of a constitution different from our sun and the generality of the fixed stars, and consist mainly of glowing gas, so far, at least, as the light-giving portion of them is concerned.

* Since writing this sentence, I have seen a note by Professor D'Arrest in the *Astronomische Nachrichten*, No. 1885. Speaking of the nebula H. IV. 37, he says: "Sein Spectrum ist ausser von Huggins bisher nur noch von Dr. H. Vogel untersucht worden. In No. 1864, *Astr. Nachr.*, theilt Letzterer mit, dass er im Jahre 1871, im Widerspruch mit Huggins' Angabe, die Linie Neb. (3)=(2), bisweilen sogar (2)<(3) gefunden habe. Nach Huggins war dagegen im Jahre 1864 positiv (2)>(3). Ist Vogel's Beobachtung, wie ich nicht bezweifle, zuverlässig, so wird seine Vermuthung einer Veränderung hier in der That begründet sein, denn diesen Winter, namentlich im Februar und März 1872, fand ich wiederum, so wie es Huggins früher gesehen hat, unzweifelhaft (2)>(3). Die relative Intensität der drei Lichtarten habe ich mehrfach in Zahlen geschätzt und erhielt z. B. in den letzten Nächten:

	März 6. März 13.	
(1)	100	100
(2)	58	63
(3)	49	52"

Waiving for the present the objections which may be urged against Mr. Stone's reasoning, let us consider the question in the light of the results afforded by actual observation.

There are not found in the spectra of different nebulae the differences of relative brightness of the bright lines and of the continuous spectrum which would be expected on Mr. Stone's hypothesis.

The star-clusters which are just within the resolving-power of the largest telescopes do not give, even faintly, a spectrum of bright lines.

The same bright lines appear to be common to all the nebulae which give a bright-line spectrum. On Mr. Stone's view, differences in the constitution of the enclosing atmospheres of different star-groups would be probable.

On this point I may be permitted, perhaps, to add the following sentences from my paper "On the Spectra of some of the Nebulae":*—

"It is indeed *possible* that suns endowed with these peculiar conditions of luminosity (giving bright-line spectra) may exist, and that these bodies are clusters of such suns. There are, however, some considerations, especially in the case of planetary nebulae, which are scarcely in accordance with the opinion that they are clusters of suns. Sir John Herschel remarks of one of this class, in reference to the absence of central condensation: 'Such an appearance would not be presented by a globular space uniformly filled with stars or luminous matter, which structure would necessarily give rise to an apparent increase of brightness towards the centre, in proportion to the thickness traversed by the visual ray. We might therefore be inclined to conclude its real constitution to be either that of a hollow spherical shell, or of a flat disk presented to us (by a highly improbable coincidence) in a plane precisely perpendicular to the visual ray.'†

"This absence of condensation admits of explanation without recourse to the supposition of a shell or flat disk, if we consider them to be masses of glowing gas. For supposing, as we probably must do, that the whole mass of the gas is luminous, yet it would follow, by the law which results from the investigations of Kirchhoff, that the light emitted by the portions of gas beyond the surface visible to us would be in great measure, if not wholly, absorbed by the portion of gas through which it would have to pass; and for this reason there would be presented to us a luminous surface only."‡

It appears, therefore, that the results of observation do not accord well with Mr. Stone's theory.

But the theory itself appears open to grave objections. It is obvious (and was strongly insisted upon by Professor Stokes in remarks made when the paper was read) that in a star-cluster in which the stars are surrounded

* *Phil. Trans.*, 1864, p. 443.

† "Outlines of Astronomy," 7th ed., p. 646.

‡ See also Sir William Herschel, *Phil. Trans.*, 1811, pp. 314, 315.

by self-luminous atmospheres, the proportion between the sum-total of the light from the stars and the light from the atmospheres will be independent of the distance of the cluster from us. Unless, then, we suppose that the light received from our own sun is but a fraction of the total light received from a supposed atmosphere of enormous extent surrounding him (a supposition which needs only to be stated to be rejected), instead of constituting the main portion of the total light, it follows that the total light received from a distant cluster formed of stars at all resembling our own sun must mainly come from the stars themselves. If, then, it be true, as it undoubtedly is, and as Mr. Stone has urged, that at a sufficient distance the light from any individual star is insignificant, while that from the cluster as a whole (both stars and atmospheres) is not, this can only be by the distance being so great that the small but finite solid angle subtended by a small portion of the slit employed in the investigation is nevertheless sufficient to take in a considerable number of the stars; and if this be admitted, Mr. Stone's reasoning falls to the ground.

NOTE ON THE PHOTOGRAPHIC SPECTRUM OF THE GREAT NEBULA IN ORION

(From *Proc. Roy. Soc.*, vol. xxxiii., p. 425, 1882)

LAST evening (March 7) I succeeded in obtaining a photograph of the spectrum of the Great Nebula in Orion, extending from a little below F to beyond M in the ultra-violet.

The same spectroscope and special arrangements, attached to the 18-inch Cassegrain telescope with metallic speculum belonging to the Royal Society, were employed which have been described in my paper on "The Photographic Spectra of Stars."*

The exposure was limited to forty-five minutes by the coming up of clouds. The opening of the slit was made wider than during my work on the stars.

The photographic plate shows a spectrum of bright lines, and also a narrower continuous spectrum which I think must be due to stellar light. The bright stars forming the trapezium in the "fish's mouth" of the nebula were kept close to the side of the slit, so that the light from the adjacent brightest part of the nebula might enter the slit.

Outside this stronger continuous spectrum I suspect an exceedingly faint trace of a continuous spectrum. In the diagram which accompanies this paper the spectrum of bright lines only is shown, which is certainly due to the light of the nebula.

In my papers on the visible spectrum of the nebula in Orion, and other

* *Phil. Trans.*, 1880, p. 672. P. 13.

nebulæ,* I found four bright lines. The brightest line, wave-length 5005, is coincident with the less refrangible component of the double line which is strongest in the spectrum of nitrogen. The second line has a wave-length of 4957 on Ångström's scale. The other two lines are coincident with two lines of hydrogen, H β or F, and H γ near G.

In the photograph these lines which had been observed in the visible spectrum are faint, but can be satisfactorily recognised and measured. In addition to these known lines the photograph shows a relatively strong line in the ultra-violet, which has a wave-length 3730, or nearly so. The wide slit does not permit of quite the same accuracy of determination of position as was possible in the case of the spectra of stars. For the same reason I cannot be certain whether this new line is really single, or is double or multiple. In the diagram this line is represented broad to indicate its great relative intensity.

This line appears to correspond to ζ of the typical spectrum of white stars. \dagger In these stars this line is less strong than the hydrogen line near G; but in the nebula it is much more intense than H γ . In the nebula the hydrogen lines F and H γ are thin and defined, while in the white stars they are broad and winged at the edges. The typical spectrum has been added, for the sake of comparison, to the diagram.

I cannot say positively that the lines of hydrogen between H γ and the line at 3730 are absent. If they exist in the spectrum of the nebula, they must be relatively very feeble. I suspect, indeed, some very faint lines at this part of the spectrum, and possibly beyond λ 3730, but I am not certain of their presence. I hope by longer exposures, and with more sensitive plates, to obtain information on this and other points. It is, perhaps, not too much to hope that the further knowledge of the spectrum of the nebulae afforded us by photography, may lead by the help of terrestrial experiments to more definite information as to the state of things existing in those bodies.

* *Phil. Trans.*, 1864, p. 437, and 1868, p. 540. Also *Proc. Roy. Soc.*, vol. xiv., p. 39, and vol. xx., p. 380.

\dagger *Phil. Trans.*, 1880, p. 677.

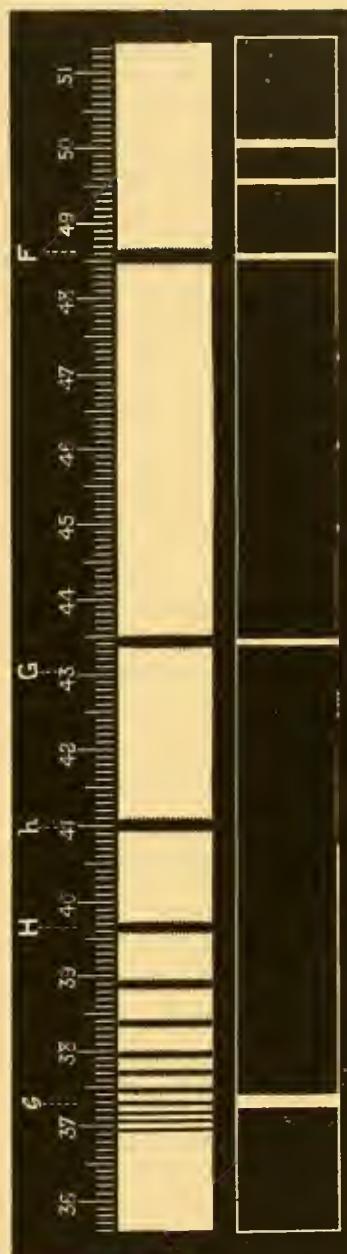


Fig. 19.

ON THE SPECTRUM, VISIBLE AND PHOTOGRAPHIC, OF THE GREAT
NEBULA IN ORION

(From *Proc. Roy. Soc.*, vol. xlvi., p. 40, 1889)

I HAVE added the name of Mrs. Huggins to the title of the paper, because she has not only assisted generally in the work, but has repeated independently the delicate observations made by eye.

In the year 1882 I had the honour to lay before the Royal Society a note on the photographic spectrum of this nebula, in which I described a new bright line in the ultra-violet, to which I gave a wave-length of about 3730. In addition to this new line, the lines of hydrogen, $H\beta$ and $H\gamma$, which I had discovered by eye in my early observations on the visible spectrum, were to be seen upon the plate.

On account of the faintness of the object the slit had been made rather wide, and for this reason the character of the line and its position, as I stated in the paper, could not be ascertained with the accuracy which I desired.

On February 5, 1888, a photograph of the spectrum of this nebula was obtained with a narrow slit; the same apparatus, so far as the essential parts, which were described in my paper on the "Photographic Spectra of the Stars,"* being employed.

In this photograph, in addition to the strong line about λ 3730, a pair of less conspicuous lines is seen on the less refrangible side of the strong line.

The continuous spectra due to the two of the four bright stars of the Trapezium which fell upon the slit are present.

Across these continuous spectra at least four groups of bright lines can be seen, of which the greater number can be traced into the nebula for some little distance from the stellar spectra.

It is scarcely necessary to state the importance of this observation as showing that these stars of the Trapezium are not merely optically connected with the nebula, but are physically bound up with it, and are very probably condensed out of the gaseous matter of the nebula. This observation would seem also to show that the nebula, as a whole, may not be at a distance from us greater than that which we should attribute to such stars, if they occurred alone in the heavens.

The first group, of six lines, occurs between λ 4116 and 4167. The lines of this group do not extend far from the continuous star spectra, with the exception of two lines. These can be seen faintly in another photograph taken in 1889. Beyond there is a fainter group, probably of four lines a little beyond λ . I am pretty sure that these lines extend into the nebula. The third group, from

* *Phil. Trans.*, 1880, p. 672.

$\lambda 3896$ to 3825 , of which I have endeavoured to measure ten lines, is faint, but here there is no doubt that the same lines are present in the adjoining nebular matter. There are two lines a little more refrangible than the strong line seen in 1882, at about $\lambda 3709$ and $\lambda 3699$. I have a suspicion of a faint group about this place, and also of another group on the less refrangible side of G.

I shall discuss further on the probable chemical significance of these lines. The lines of this photograph are shown in Spectrum No. 1 of the folding Plate.

During the time that Orion was favourably situated for observation in the season of 1888 and in that of the present year, the unusual continuance of bad weather has made it impossible for me to give so complete an account of the spectrum of the nebula in the photographic region as a few really fine nights would have enabled me to do. However, on February 28 of the present year I obtained another photograph, the slit being very narrow, which gives some more new information on the nature of its spectrum. I was astonished on looking at the photograph not to see the strong line about $\lambda 3730$, which was by far the most conspicuous feature of the photograph taken in 1888. The pair of lines near it on the less refrangible side, which I found for the first time in 1888, are present; and on a further scrutiny of the plate I discovered two other pairs of lines, most probably rhythmically connected with them, in the still more refrangible region, the last pair, accompanied by a third line, being near the ultra-violet limit of ex-terrestrial light.*

I was also able to see faintly two of the bright lines which I have described as present across the continuous spectra of the brighter stars of the Trapezium in my photograph of 1888. It is not quite certain whether these very faint and short lines are really due to the matter of the nebula proper, or have come upon the plate in consequence of the stars of the Trapezium having fallen accidentally upon the slit for a time too short to impress the continuous part of their spectra. No trace of a continuous spectrum can be seen upon the plate, but these lines in the plate of 1888 do extend beyond the continuous spectra of the stars of the Trapezium.

In the diagram which follows I have indicated the positions of the slit upon the nebula relatively to the Trapezium and the well-known three stars near it, for the photographs of 1882, 1888, and 1889.

I regret extremely that bad weather has made it impossible for me to work out the circumstances on which depended the disappearance of the strong line about $\lambda 3730$. Both the photographs which show this line include two stars of the Trapezium, and it may possibly be that this strong line is associated with the groups near it in the spectra of the stars, and may therefore come out in those parts of the nebula only which are more condensed. A few photo-

* "On the Limit of Solar and Stellar Light in the Ultra-violet Part of the Spectrum," p. 80.

graphs with the slit differently placed upon the nebula would doubtless have thrown light upon this point. The suggestion presents itself strongly that the mottled and broken-up character of the nebular matter, shown in Lord Rosse's drawing from eye observations, and much more strikingly brought out in the recent photographs of Mr. Common and Mr. Roberts, may be connected with differences of spectrum in the photographic region, though in the visible region

there is no known alteration of the spectrum of the four bright lines, except, it may be, some small differences of relative brilliancy of the lines.

Until next winter we cannot go beyond the new information which these photographs give to us. On the plate of the photograph of 1889 two pairs of spectra for comparison were taken: two spectra, one above and one below the nebular spectrum, of burning magnesium; and two spectra, similarly placed, of the light of the sky.

From the photographs of 1888, taken with a narrow slit, the position which I gave in 1882 to this line is shown to be, as I expected from the wide slit then used, approximate only. I find from the later photograph that the wide slit had caused the strong line to unite with a line near it, and that in 1882 I measured the middle of the broad band produced by the union of the wide images of two lines.

Its position is about six tenth-

metres more refrangible. It does not therefore agree, as I then suggested, with the hydrogen line ζ in my spectra of white stars. A statement of the position of this line relatively to the magnesium-flame triplet will be given further on, when I come to discuss the comparison of this spectrum with that of the nebula.

The position of the pair of lines a little less refrangible than this strong

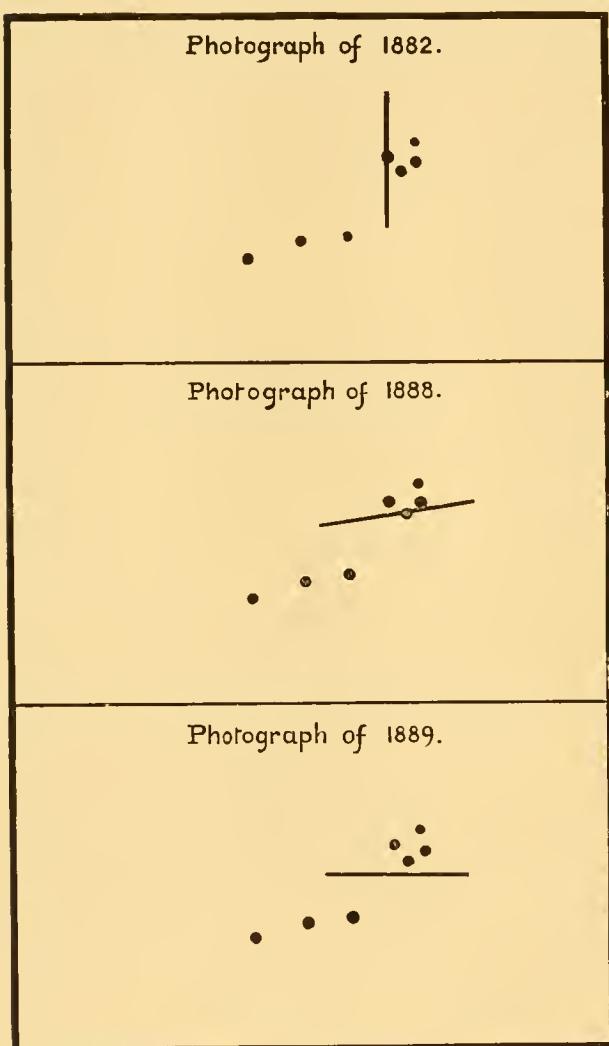


Fig. 20.

line, seen with it in the photograph of 1888, and present without the strong line in the photograph of 1889, and the positions of the two other more refrangible pairs, presumably connected with the first pair, are given in the following table:—

1st pair about	λ	3752°
		{ 3741°
2nd pair about		{ 3285°
		{ 3275°
Line at about		3060°
3rd pair about		{ 3053°
		{ 3047°

These three pairs of lines are shown in Spectrum No. 3 of the Plate.

In both photographs I suspect the indications of other lines, which are too faint to permit any certain conclusion to be formed about them, whether they are true lines, or imperfections only of the film.

[The continuous spectra of the stars of the Trapezium can be seen on the plate from about F to λ 3574; but they are very faint beyond λ 3660.—May 7.]

THE VISIBLE SPECTRUM

(a) *Brightest line.*—In 1872* I stated, as the result of numerous direct comparisons of this line with the brightest line in the spectrum of nitrogen, that the nebular line was “sensibly coincident with the middle of the less refrangible line of the double line of nitrogen.” To avoid repetition I will call this line N_1 . Except where it is otherwise stated, I use this line of nitrogen simply as a fiducial point in the spectrum, without any reference to its chemical significance.

In a still more critical examination of the position of the nebular line, for the purpose of determining whether there was any indication of relative motions of the gaseous nebulae in the line of sight, I found some experimental difficulty from the circumstance that the nebular line is narrow and defined while N_1 is nebulous. I was fortunate to find a more suitable fiducial line of comparison in a narrow line of lead which falls almost upon the middle of N_1 .† In December 1872, I compared this line directly with N_1 , and found it sufficiently near in position to serve as a fiducial line of comparison.

Six other gaseous nebulae were also examined, each on several nights, with the result that “in no instance was any change of relative position of the nebular line and the lead line detected.”‡

* “On the Spectrum of the Great Nebula in Orion, etc.,” *Proc. Roy. Soc.*, vol. xx., 1872, p. 383.

† “On the Motions of some of the Nebulae towards or from the Earth” (*Proc. Roy. Soc.*, vol. xxii., 1874, p. 252).

‡ *Ibid.*, p. 253.

In the simultaneous observation of the nebular line and the lead line it was found if the lead line was made rather less bright than the line of the nebula, the small excess of apparent breadth of this latter line appeared to overlap the lead line to a very small amount on its less refrangible side, so that the more refrangible sides of the two lines appeared to be in a straight line across the spectrum. The closeness of position of the two lines was shown by the observation that when the line of the nebula passed across the field of the spectroscope, and the lead line was thrown in, the lead line was not seen, but only an increase in brightness of the nebular line. By comparing the end of the nebular line near the Trapezium where it is refined to a point, I estimated that the difference of position of the middle of the lead line and that of the nebular line might be possibly from $\lambda 0000\cdot2$ to $\lambda 0000\cdot3$.* Some recent measures of the position of the lead line with the middle of N_1 show that the lead line is about $\lambda 0000\cdot12$ more refrangible.

These direct comparisons of the nebular line with the lead line confirmed, therefore, my former conclusion, that the brightest line in the gaseous nebulæ is very near N_1 , when seen under a dispersion equal to nearly eight prisms of 60, namely, $36^\circ 25'$ from A to H.

This result is based on direct comparisons, on twenty-four different nights, with N_1 or with the line of lead.

The wave-length of N_1 has been determined by Kirchhoff, Thalén, and by myself. Watts' reduction of my measure to wave-lengths is clearly not accordant with my measures of air lines immediately preceding and following this line. I have therefore reduced my original measure to wave-lengths, and find for N_1 the value $\lambda 5004\cdot5$.

Kirchhoff	5004·6
Thalén	5005·1

Thalén's value is clearly too high, as Thalén gives for the lead line coincident nearly with N_1 $\lambda 5004\cdot6$, and N_1 is seen on the more refrangible side of the solar iron line given by Ångström as $\lambda 5004\cdot9$. In Ångström's map N_1 is laid down on the more refrangible side of the iron line 5004·9, at about 5004·5. The same position is given to N_1 in Kirchhoff's map.

I have made a new determination of the position of N_1 , using the second spectrum of a grating 17,300 to the inch, relatively to the solar iron line at 5004·9 according to Ångström.

The value came out $\lambda 5004\cdot6$, which agrees with Kirchhoff's value, and with Thalén's measure of the lead line which falls upon it, and also with the maps of Ångström and of Kirchhoff.

* "On the Motions of some of the Nebulæ towards or from the Earth" (*Proc. Roy. Soc.*, vol. xxii., 1874, p. 252).

The wave-length of the brightest nebular line may therefore be taken at from

$$\lambda 5004\cdot6 \text{ to } \lambda 5004\cdot8 \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The micrometric measures of this line, given by D'Arrest, Vogel, and Copeland, agree closely with this value.

D'Arrest's* mean value	$\lambda 5004$
Vogel's	"	5004
Copeland's†	"	5004

(b) *Second line*.—In 1872,‡ I stated that I had found this line, by comparison with a line of barium and subsequently with an iron line, to have

A wave-length of	$\lambda 4957\cdot0$.	.	(2)
D'Arrest's mean value from micrometric measures						$4956\cdot6$			
Copeland's	"	"	"			$4958\cdot0$ §			

(c) *Third line*.—In my original paper || “On the Spectra of some of the Nebulæ,” in 1864, I showed, by direct comparison with hydrogen, that this line is undoubtedly the line of that gas at F of the solar spectrum. This observation was afterwards repeated,¶ and has been confirmed by the photographs of 1882 and 1888.

The wave-length of this line is therefore	.	.	$\lambda 4860\cdot7$.	.	.	(3)
D'Arrest's value from measures	.	.		$4860\cdot6$			
Copeland's	"	"		$4861\cdot0$			

(d) *Fourth line*.—In 1872,** I stated that I had satisfied myself of the coincidence of this line with H γ , but, on account of its faintness, it is very satisfactory to find this observation of coincidence confirmed by the photographs taken in 1888 and 1889. There can be no doubt that this is a line of hydrogen, and that

The wave-length therefore is	$\lambda 4340\cdot1$.	.	(4)
Copeland's mean value	$4342\cdot0$			

Dr. Copeland gives the measures of two still fainter lines which he has seen in this nebula—namely, one at $\lambda 5874$, possibly coincident with D₃, and a line at $\lambda 4476$. (See also Mr. Taylor, *Monthly Notices R.A.S.*, vol. xlix., p. 125.)

I defer the consideration of these and other faint lines which I have often suspected in the faint continuous spectrum of the nebula, as in consequence of the great strain upon the eyes from my recent direct comparison of the spectrum of the nebula with the spectrum of burning magnesium, I was not

* “Undersögelse over de nebulose Stjerner.” Copenhagen, 1872, p. 23.

† *Monthly Notices R.A.S.*, vol. xlvi., p. 361. ‡ *Proc. Roy. Soc.*, vol. xx., 1872, p. 385.

§ For the final positions of the first and second lines, see p. 186. || *Phil. Trans.*, 1864, p. 437.

¶ *Ibid.*, 1868, p. 545. ** *Proc. Roy. Soc.*, vol. xx., 1872, p. 385.

able during the very few fine nights when Orion was favourably situated to undertake an examination for these very faint lines.

COMPARISONS WITH THE MAGNESIUM-FLAME SPECTRUM

In 1882, Dr. Copeland, in his paper on Schmidt's Nova Cygni,* remarked, in a footnote, "that it is worthy of note that this line (λ 5006·5 of burning magnesium) almost absolutely coincides with the brightest line in the planetary nebulae."

This line, namely, the bright edge of the first band in the magnesium-flame spectrum, is very near in position to the brightest nebular line. We have seen that the wave-length of this line in the nebulae (1) is 5004·6 to 5004·8; now the wave-length of the end of the magnesium-flame band is 5006·5, consequently it does not coincide with the nebular line, but falls on the less refrangible side at a distance of λ ·0002 nearly from that line.

The wave-length of the termination of the magnesium-flame band is, as determined by—

Lecoq de Boisbaudran	λ 5006·0
Watts	5006·5
Liveing and Dewar †	5006·4

I have recently redetermined the position of the end of the band, by direct comparison with the solar iron line given by Ångström at λ 5006·58.

My result places the magnesium-flame band line at λ 5006·5

In a paper read before the Royal Society in 1887,‡ Mr. Lockyer says: "Only seven lines in all have been recorded up to the present in the spectra of nebulae, three of which coincide with lines in the spectrum of hydrogen and three correspond to lines in magnesium. The magnesium lines represented are the ultra-violet low-temperature line at 373, the line at 470 and the remnant of the magnesium fluting at 500, the brightest part of the spectrum at the temperature of the Bunsen burner." At page 137 (*loc. cit.*) Mr. Lockyer says: "In the nebulae we deal chiefly with lines seen in the spectrum of magnesium at the lowest temperature."

In a later paper in 1888 § Mr. Lockyer states: "In a paper communicated to the Royal Society on November 15, 1887, I showed that the nebulae are composed of sparse meteorites, the collisions of which bring about a rise of

* "Copernicus," vol. i., p. 109.

† *Proc. Roy. Soc.*, vol. xliv., 1888, p. 245.

‡ "Researches on the Spectra of Meteorites: a Report to the Solar Physics Committee; communicated to the Royal Society at the request of the Committee" (*Proc. Roy. Soc.*, vol. xliv., p. 118).

§ "Suggestions on the Classification of the various Species of Heavenly Bodies" (*Proc. Roy. Soc.*, vol. xliv., p. 21).

temperature sufficient to render luminous one of their chief constituents—magnesium. This conclusion was arrived at from the facts that the chief nebular lines are coincident in position with the fluting and lines visible in the Bunsen burner when magnesium is introduced, and that the fluting is far brighter at that temperature than almost any other spectral line or fluting of any element whatever."

Although the number of direct comparisons which I have made of the brightest line in the nebulae with N_1 and with the lead line, not to speak of the accordant results of the micrometric measures of other observers, left great doubt in my mind whether this line could be coincident with "the remnant of the magnesium fluting at 500," really at 5006·5, yet I thought it desirable to undertake the laborious task of comparing, with the necessary care and precautions, the nebular line directly, in the spectroscope attached to the telescope, with the spectrum of burning magnesium.

Arrangements were made by which the light from burning magnesium was thrown into the telescope from the side and then reflected down, under conditions similar with the light from the nebula, upon the slit of the spectroscope. By this arrangement any flexure in the tube connecting the spectroscope with the telescope would affect both spectra alike. The coincidence in position of the spectrum from burning magnesium with that of a heavenly body to which the telescope was so directed that its light fell upon the slit of the spectroscope was tested with great care on several occasions by comparing the three bright lines of magnesium with the corresponding lines, b_1 , b_2 , b_4 , in the spectrum of the moon. Indeed, to prevent any possible error in the observation of apparent want of coincidence of the nebular line, if the light from the burning magnesium should by an accident so come upon the slit as to bring its spectrum in a very minute degree on the less refrangible side of its true position relatively to the nebular line to be observed with it, the arrangement was purposely made that the lines of magnesium were seen to fall upon the corresponding dark lines at b in the moon, a very little on the more refrangible side of the middle of those lines. This state of things would diminish a little the interval which should be seen between the nebular line and the edge of the magnesium-flame band, and so make the determination more difficult; but if under such circumstances the nebular line was seen on the more refrangible side of that of magnesium the observation would be much more trustworthy, for in the case of coincidence with magnesium the line would have appeared towards the opposite and less refrangible side of the magnesium line, broadening the magnesium line on this side. I considered that the comparison could be made most satisfactorily by the complete superposition of the two spectra, that from burning magnesium being gradually reduced in brightness by the interposition of coloured glass screens, until the ground of the spectrum between the successive

bright lines of the band of the magnesium-flame spectrum was sufficiently subdued to allow of the nebular line being seen upon it.

Under these circumstances, if the nebular line had the position which my direct comparisons and the micrometric observations of other observers assign to it, it would be seen as a bright line at a very small interval within the line ending the band, and to the observer the band would appear to commence with a double line.

The direct comparison was first successfully made on March 6, 1889. The observations were made with the 15" refractor belonging to the Royal Society. The spectroscope used has two compound Grubb prisms, each with 5 square inches of base, and giving nearly twice the dispersion of a single prism of 60° , namely $9^\circ 20'$ from A to H; and collimator and telescope of 1.25-inch aperture. An eyepiece magnifying eighteen times was employed. The nebular line was brought upon the cross-wires, and when carefully focussed and clearly seen, the light from burning magnesium was thrown in. This observation is one of great difficulty, especially as the interval to be observed had been purposely reduced by causing the magnesium to fall, for the sake of the greater trustworthiness of the observations, on the more refrangible side of its true position. Although I consider the results to be satisfactory, I prefer to say that I, and Mrs. Huggins independently, believed fully at the time that we saw the appearance which all former observations of this line led me to expect—namely, the nebular line to fall within the termination of the magnesium band, and to form with the band-boundary a double line. The relative positions of the two spectra are represented in the diagram across the page. The line at the end of the magnesium band was then brought upon the cross-wires, without any attention being given to the nebular line; when the burning magnesium went out, the nebular line was seen to be at a measurable distance to the left of the intersection of the wires, namely, on the more refrangible side.

When the object-glass of the telescope was covered, the magnesium band presented its usual appearance, namely, terminating in a single line. These comparisons were repeated and confirmed generally on March 9, March 11, and March 16. On March 9 a single successful comparison was made with a more powerful spectroscope, giving a dispersion equal to nearly eight prisms of 60° . [Comparisons have been made since with the planetary nebula in Hydra. The short line of the nebula was found to fall within the termination of the magnesium band at about the small distance which corresponds to the known position of the two lines.—April 26.] On all these nights the comparisons were repeated independently and fully confirmed by Mrs. Huggins.

These comparisons can be successfully imitated in the laboratory by directing a spectroscope of sufficient power to the line of lead which the nebular line is sufficiently near, the slit being narrow and the electrodes of lead near

each other; and then causing, with the necessary precautions, the light of burning magnesium to fall also upon the slit. The lead line will be seen to fall within the end of the band, and to form with it a double line.

It may be mentioned in this place that this line of lead, and the iron line at 4957 at the position of the second nebular line, can be conveniently used in the laboratory in any chemical research on the nature of the nebulae. No terrestrial line which does not fall almost exactly at these positions in the spectrum can have any claim to further consideration.

It might be suggested that the want of coincidence observed between the nebular line and the magnesium band, amounting to $\lambda 0001.9$ nearly, might be due to a motion of translation of the nebula towards the earth. The motion required to produce this shift of position is about 67 miles in a second.

[The earth's motion at the time of comparison with the magnesium-flame band may be taken at about 17 miles in a second of recession from the nebula. This motion would bring the nebular line nearer the red, and diminish the apparent interval between that line and the termination of the band. If the nebula has a motion of approach, the earth's recession would bring the line back again, to an extent corresponding to about 17 miles in a second, towards its true place.—May 13.]

I showed in my paper on this subject in 1874,* that in the case of the Orion nebula and six other gaseous nebulae—namely, 4234, 4373, 4390, 4447, 4510, 4964, of Sir J. Herschel's "General Catalogue of Nebulæ"—"in no instance was any change of relative position of the nebular line and the lead line detected." We should have to resort, therefore, to the overwhelmingly improbable supposition that all seven nebulae were approaching the earth with velocities such that, having respect to the earth's motion at the different times of observation, they all gave a sensible shift corresponding to 67 ± 15 miles in a second. There is little doubt in my mind, therefore, from these comparisons,

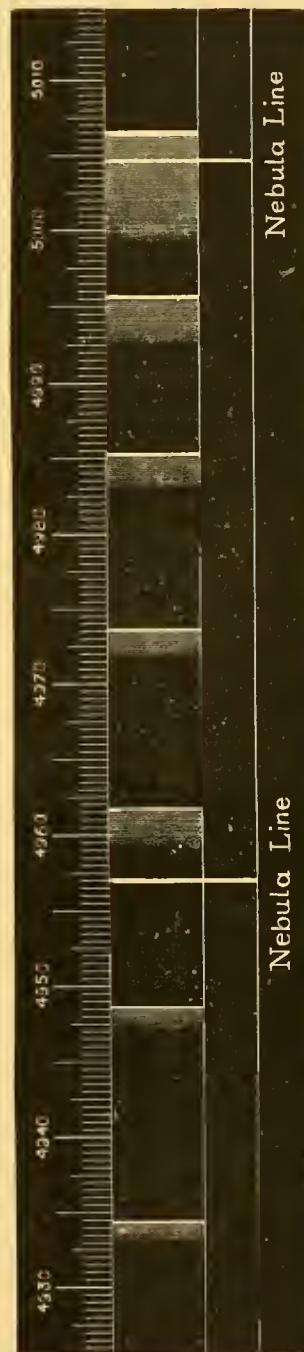


Fig. 21.

* *Proc. Roy. Soc., vol. xxii., p. 253.*

which, considering the strong evidence we possessed before of the relative positions of the nebular line and of the magnesium line, are strictly speaking supplementary and confirmatory evidence only, that this line of the gaseous nebulae is not produced by "the remnant of the magnesium fluting."*

In the diagram on page 134 (*Proc. Roy. Soc.*, vol. xliii.), Mr. Lockyer represents this nebular line followed by fine lines, which gives it the appearance of a fluting similar to that of the magnesium band placed above. I am unable to find in the paper any authority for this representation of the line. In another place † Mr. Lockyer says: "On one occasion, at Greenwich, it was recorded as a fluting in the spectrum of the nebula in Orion." Mr. Maunder's words are: ‡ "None of the lines" (with two-prism train) "are very sharp. λ 5005 showed a faint fringe mainly on the side nearer the blue."

Mr. Maunder has recently sent a note to the Royal Astronomical Society, in which he explains that the observation was made with a second half-prism added to the half-prism spectroscope. He says: "The three principal lines of the nebular spectrum were seen as very narrow bright lines, but none of them were perfectly sharp, each showed a slight raggedness at both edges; but in the case of the line near λ 5005 it was clear that this fringe, or raggedness, was more developed towards the blue than towards the red. In the case of the

* [The following observations were made at Greenwich in 1884 on the motion of the nebula in the line of sight:—

"February 15. Mean of four observations, 31 miles of approach."

Remarks: Measures purely tentative.

"February 18. Mean of four observations, 51 miles of approach."

Remarks: The F line in the spectrum of the nebula was faint, very much fainter than the line at λ 5005. The measures, therefore, are not trustworthy.

"March 10. With neither one nor two prism trains, after very careful direct comparison (the light from the comparison tube being weakened until it could be compared directly with the light from the nebula), could any displacement be detected; the coincidence of two spectra was evidently very close.

"March 12. Spectrum too faint for measures. The hydrogen spectrum was brought down to almost exactly the same intensity as the light from the nebula, and direct comparison showed coincidence as complete as could be detected considering the faintness of the two spectra. . . . No part of the nebula which was sufficiently bright to show the pointer well on the 5005 line showed any marked displacement, but at a point a little preceding the Trapezium it was thought that the pointer did not seem perfectly central on the line but a little (perhaps $\frac{1}{10}$, certainly not more) towards the red."—"Greenwich Spectroscopic and Photographic Results," 1884.

Also in 1887, six determinations on the same night:

				Estimated		
"Oct. 25.	Measured	37·8	miles of approach.	24·0	miles of approach.	
"	"	8·3	" recession.	"	9·3	" recession.
"	"	7·1	" .	"	9·3	" "
"	"	38·4	approach.	"	24·0	" approach.
"	"	24·5	"	"	24·0	" "
"	"	10·8	recession.	"	9·3	" recession.

Remarks: Lines in nebula very faint and bisections very rough."

"Greenwich Spectroscopic and Photographic Results," 1887.—May 13.]

† Programme Royal Society Soirée, May 9, 1888, p. 12.

‡ "Greenwich Spectroscopic Results," 1884, p. 5.

other two lines, they were not bright enough for it to be possible to ascertain whether the fringes were symmetrical or not. But λ 5005 was clearly a single line. There was no trace of any bright line, or series of bright lines, close to it on either side; no trace of a fluting, properly so called. The entire line, fringes and all, was only a fraction of a tenth metre in total breadth.”*

[It should be noticed that the instrumental conditions under which Mr. Maunder observed showed the second and third line “not perfectly sharp, but with a slight raggedness at both edges.”—May 13.]

My own observations of this line, since my discovery of it in 1864, with different spectrosopes up to a dispersion equal to eight prisms of 60° , show the line to become narrow as the slit is made narrow, and to be sharply and perfectly defined at both edges.

As some importance attaches to the precise character of this line, I wrote to Professor H. C. Vogel for permission to quote the result of his experience, which has been nearly as long as my own, of the character of this line. He says in his reply, dated March 20, 1889: “Beeile ich mich Ihnen mitzutheilen, dass meine langjährigen Beobachtungen über die Spectra der Gas-Nebel vollkommen mit den Ihrigen darin übereinstimmen, dass die Nebellinie λ 5004 schmal, scharf und nicht verwaschen ist. Auch D'Arrest hat in seiner Untersuchung über die Nebel-Spectra (Kopenhagen, 1872) nicht erwähnt dass die hellste Nebellinie unscharf sei.”

Dr. Copeland permits me to quote the following sentences of a letter dated March 19, 1889: “Respecting the appearance of the line λ 5004 in the spectrum of the Orion nebula, I may say that I have always drawn and seen it quite sharp and well defined on both edges. About nine years ago I made a special effort to divide it, if possible, with a large spectroscope in which the viewing telescope was 3 inches in aperture. The lines were then seen as sketched.” (The diagram shows the nebular lines with sharply ruled lines for edges.) “They were drawn by holding the note-book 10 inches from the left eye, in such a position that the image seen in the instrument with the right eye was apparently projected on the paper. If I had noticed any peculiarity about λ 5004, it would certainly have been noted.”†

In an early observation of the Dumb-bell nebula Professor Vogel, indeed

* *Monthly Notices R.A.S.*, vol. xlix., 1889, p. 308.

† Mr. Taylor, late of the South Kensington Laboratories, observing at Sir Henry Thompson's observatory in November 1888, says: “The 5001 line is by far the brightest in the spectrum. It is never seen sharp, but with the narrowest slit always has a fluffy appearance, this being much more marked on the blue than on the red edge. This line was most carefully examined for evidence of structure, but was always found to be single, and no decided evidence of fluting structure could be made out. It may be that greater dispersion may show structure, but with the dispersion used here no structure could be seen.”—*Monthly Notices R.A.S.*, vol. xlix., p. 125.

("Beobachtungen zu Bothkamp," p. 59, 1872), describes this line as less defined towards the violet side. In a letter (April 3, 1889) Professor Vogel says this appearance of the line was probably due to a slit not sufficiently narrow. He says that he re-examined this line in his observations with the great Vienna refractor, and that it did not then appear otherwise than defined and narrow.

The other line in the spectrum of the nebulae upon which Mr. Lockyer mainly relies for the presence of magnesium is the line shown in my photographic spectrum of 1882,* and to which I assigned the wave-length of about 3730. Mr. Lockyer says of this line: † "In the Bunsen as ordinarily employed the fluting at 500 far eclipses the other parts of the spectrum in brilliancy, and at this temperature, as already observed by Messrs. Liveing and Dewar, the ultra-violet line visible is that at 373." Passing by a minor point, which Liveing and Dewar have already pointed out,‡ namely, that their observation was made at the higher temperature or burning magnesium, this statement is insufficiently complete, for what occurs at this part of the

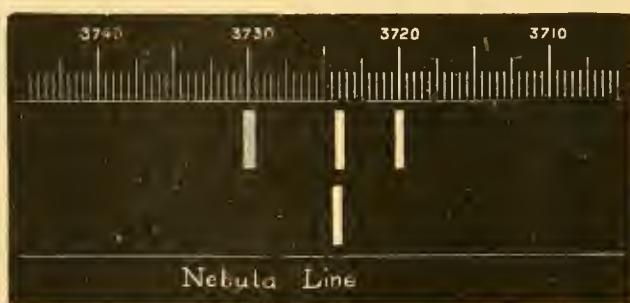


Fig. 22.

spectrum, and is characteristic of the magnesium-flame spectrum, is a triplet, of which the line given by Liveing and Dewar at about 3730 is the least refrangible member.

In the accompanying diagram I give a representation of this triplet at the wave-lengths given by Liveing and Dewar, namely λ 3730, 3724, and 3720. In the photograph of 1888, in which the strong line can be seen distinct from the lines near it, the line is found to be very near the middle line of the triplet. I have therefore assigned to this line the position of about λ 3724. This line appears pretty strong, and therefore if it were really one of the lines of the triplet, the other two members of the triplet should have appeared on the plate. On one side of the star-spectra this line is a little broader than on the other side, but as a similar appearance is presented by G, and the stronger of the lines of the group, it may arise from some optical or photographic cause. The line at 3724 impresses me strongly as a single line, and there is certainly no trace of

* *Proc. Roy. Soc.*, vol. xxxiii., p. 425.

† *Ibid.*, vol. xliv., 1887, p. 122.

‡ *Ibid.*, vol. xliv., 1888, p. 244.

the first line of the triplet at 3730. The line appears to me stronger where it is upon the star-spectra.

As therefore there seems to be little doubt that the "remnant of the fluting at 500" is not coincident with the brightest nebular line, and the next most characteristic group of this spectrum, the triplet at 3720, 3724, and 3730, according to Liveing and Dewar, does not appear to be present in the photographs, we may conclude that the remarkable spectrum of the gaseous nebulae has not been produced by burning magnesium.*

I should mention that Mr. Lockyer attributes one other line occasionally seen in the gaseous nebulae to the flame spectrum of magnesium—namely, a very faint line at about λ 4700. Now, according to my experience, it is only in the spark and arc that a line of magnesium appears at this place, a condition of the spectrum when the lines at *b* are very conspicuous, and the band at λ 5006·5 is usually absent. When, however, the spark is taken in magnesium chloride, the band is present under some conditions, but the triplet at *b* is always bright. I therefore consulted Professor Liveing, who says: "I have never seen the line at λ 4703 in the spectrum of the magnesium flame. As it is a conspicuous line in the arc and spark, we looked for it in the flame, but did not find it."

With reference to the second nebular line at λ 4957, Mr. Lockyer says: † "The lines at 500 and 495 have been seen in the glow of the Dhurmsala meteorite when heated, but the origin of 495 has not yet been determined." And further (at p. 135): "I should add that the line at 495 makes its appearance much more rarely than the one at 500 in meteorite glows." In the diagram on the same page this line is represented as coincident with the nebular line.

The circumstance of a line appearing at 495 can scarcely be regarded, considering the very great number of spectral lines, as amounting to a presumption that the material to which it is due in the meteorite is the same as that present in the nebulae which gives the line at 4957. If it should be shown

* On the narrower basis of the magnesium spectrum only, Professors Liveing and Dewar point out that: "the appearance of a line in the position of the first band without any trace of the second band, which is nearly as bright as the first, and without any trace of the *b* group, is quite sufficient to create a suspicion of mistaken identity when Mr. Lockyer ascribes the sharp green line in the spectrum of nebulae to this band of magnesia. This suspicion will be strengthened when it is noticed that the line in question is usually in nebulae associated with the F line of hydrogen, if it be borne in mind that the spark of magnesium in hydrogen does not give the bands, and that the oxyhydrogen flame hardly produces them from magnesia when the hydrogen is in excess" (*Proc. Roy. Soc.*, vol. xliv., p. 245). Mr. Taylor records a brightening of the continuous spectrum of the nebula at λ 5200, which he suggests may be magnesium. But this position is twenty-five units from that of the middle of the magnesium triplet at "*b*" (*Monthly Notices R.A.S.*, vol. xlix., p. 125).

† *Proc. Roy. Soc.*, vol. xliii., p. 133.

that the unknown substance in the meteorite gives rise to a line at the position of the nebular line, namely, λ 4957, in that case the observation would have sufficient importance to make it desirable to compare the spectrum of the meteorite directly with that of the nebula.

LINES OBSERVED AND PHOTOGRAPHED IN THE SPECTRUM OF THE NEBULA

Line measured by Dr. Copeland, probably D ₃	.	λ 5874°
Brightest line	5004·6 to 5004·8
Second line	4957°
Third line, H β	4860·7
Fourth line, H γ	4340·1
Line measured by Dr. Copeland	4476°
Strong line in photographs 1882 and 1888 about		3724°
Line in photographs 1888 ,		3709°
" "		3699°
Photograph 1889. 1st pair .	{ about .	3752°
" 2nd pair .	{ " .	3285°
Line at	3275°
" 3rd pair .	{ " .	3060°
Photograph 1888	{ " .	3053°
Lines across star spectra, 1st group	{ " .	3047°
2nd group	{ " .	4116°
3rd group	{ " .	4123°
	{ " .	4130°
	{ " .	4142°
	{ " .	4154°
	{ " .	4167°
	approximate	λ 3998°
	"	3988°
	"	3975°
	"	3959°
	"	3896°
	"	3887°
	"	3878°
	"	3870°
	"	3859°
	"	3854°
	"	3848°
	"	3842°
	"	3832°
	"	3825°

CHEMICAL SIGNIFICANCE OF THE LINES

Until I can obtain more photographs taken on different parts of the nebula, I wish to be understood to speak on this point with much hesitation, and provisionally only. We know certainly that two of the lines are produced by hydrogen. The fineness of these lines points to a high temperature and condition of great tenuity of the hydrogen from which the light was

emitted. This condition of the hydrogen may give us a clue as to the probable interpretation of the other lines. These may come from substances of very low vapour-density, and under molecular conditions which are consistent with a high temperature. It is in accordance with this view that the recent measures of Dr. Copeland, since confirmed by Mr. Taylor (*loc. cit.*), show with great probability that the line known as D₃, which has been supposed to indicate some substance of low vapour-density, which shows itself only at the hottest region of the sun, is present in the nebular spectrum. The great simplicity of the three pairs of lines seen in the photograph of 1889 suggests a substance of a similar chemical nature.

If hydrogen can exist at half its usual vapour-density, with a molecule of one atom only, we might possibly expect to find it in some of these bodies, but at present we do not know what its spectrum would be in such a condition. It may be, possibly, that it is in molecular states of our elements other than those we are acquainted with that we may have to look for an interpretation of some of the lines of these bodies.

[With respect to the groups of lines which cross the star spectra, any statements must also be provisional only.

These lines are distinct and fairly strong in the star spectra, and extend, some farther than others, into the adjoining nebular matter. Whether they are peculiar to these particular stars and the matter close about them, or whether they will be found everywhere in the nebula, or in certain parts of greater condensation only, can be known only from future photographs.

The first group shows some general agreements with a strong iron group, but there are also formidable discrepancies.

The position of the third group suggested the well-known cyanogen group, especially as this group, beginning at λ 3883, is the first to appear under the chemical conditions which might have been conceived to exist under circumstances of condensation.* Under these conditions this group appears alone in a photograph, without the less refrangible group, as was probably the case in the photograph I took of Comet II, 1881. I therefore took a photograph of an oxy-coal-gas flame, the coal-gas having passed through ammonia, and a magnesium-flame spectrum on the same plate for comparison.

On comparing this photograph with that of the nebula, it was seen by eye, and afterwards confirmed by measurement, that the nebula group begins sooner by one strong line than the cyanogen group, and presents besides in the relative strength and grouping of the lines a distinctly different character. The evidence appears to me to be against attributing these lines to cyanogen.

I took great pains to ascertain if the group of lines which accompanies

* See Liveing and Dewar, *Proc. Roy. Soc.*, vol. xxxiv., 1883, p. 128.

the triplet of the magnesium-flame spectrum could be made to agree with the much longer group of lines in the nebula at this part of the spectrum. Again, as in the case of the cyanogen group, the whole aspect of the grouping of lines is quite different. The groups begin and end differently, and the relative strength of different parts of the group is not the same. The great increase of strength which is seen in the middle of the magnesium group is not present at the corresponding part of the nebula group. I do not think, therefore, there should be much weight given to the near positions of several individual lines of the two groups, which in the case of so close a grouping might well be accidental, especially as the wave-lengths can be but approximate only.

[The strongest lines of the magnesium-flame group are those forming the triplet which appears also in the spark and the arc spectrum. A nebular line is near the middle line of the triplet, but there are no lines corresponding to the other two lines of the triplet. The other lines of the flame group are too faint to be expected to appear, unless the triplet at 3720—3730 were strong upon the plate.—May 13.]

The three pairs of lines in the photograph of 1889, which are doubtless rhythmically connected, appear to me to possess great interest, especially if it should come to be found from future photographs that these groups are characteristic of the most tenuous part of the nebula. At present, I am not able to make any suggestion as to their chemical origin, but the suggestion presents itself that we may have to do with some molecule of low vapour-density.

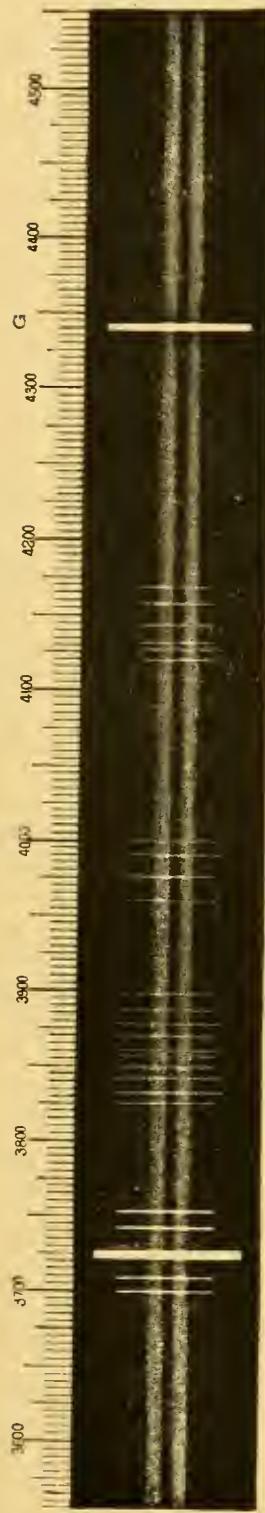
The pair of lines on the more refrangible side of the line at λ 3724 may possibly be connected with the state of the nebula as it exists in the neighbourhood of the stars.—April 26.]

GENERAL CONCLUSIONS

It seems to me premature, until we can learn more of the significance of the new groups of lines, and especially of their connection with the nebular matter generally, or with certain condensed parts only, to express more than provisional suggestions as to the nature of these nebulæ. It may be that they represent an early stage in the evolutionary changes of the heavenly bodies.

As some physical importance, in the relation of these nebulæ to each other, has been given to my inability, in consequence of insufficient optical means in my original observations in 1864, to see all three of the bright lines in some faint nebulæ, I may mention that in the case of one object, the Ring Nebula in Lyra, in which at that time the light appeared monochromatic, as only the

Photograph of 1888.



Visible Spectrum.



Photograph of 1889.

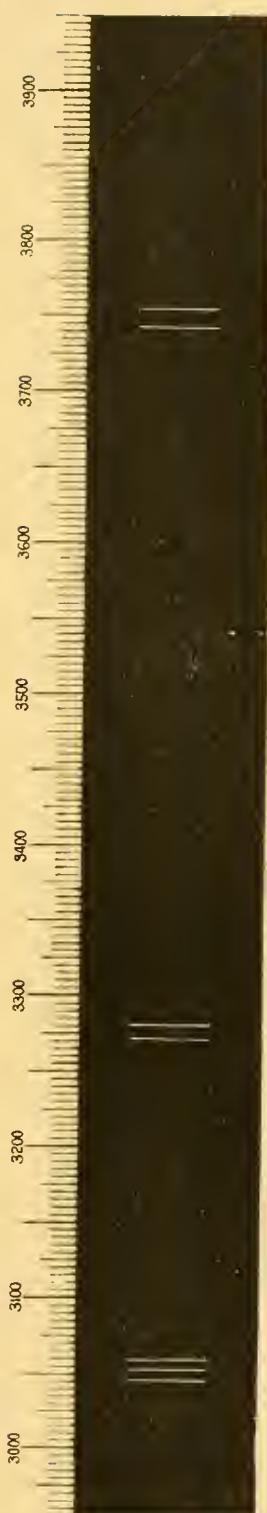


Fig. 23

brightest line could be certainly seen, as soon as larger means were placed at my disposal by the loan of the Royal Society telescope in 1870, I had no difficulty in seeing all three lines on any night of sufficient clearness. There is little doubt that the same cause prevented me from seeing more than the brightest line in Nebula 4572 of Herschel's "General Catalogue." Vogel saw two lines.*

These bodies may stand at or near the beginning of the evolutionary cycle, so far as we can know it. They consist probably of gas at a high temperature and very tenuous, where chemical dissociation exists, and the constituents of the mass, doubtless, are arranged in the order of vapour-density. As to the conditions which may have been anterior to this state of things, the spectroscope is silent. We are free, so far as the spectroscope can inform us, to adopt the hypothesis which other considerations may make most probable. On Dr. Croll's † form of the impact theory of stellar evolution, which begins by assuming the existence of stellar masses in motion, and considers all subsequent evolutional stages to follow from the energy of this motion converted into heat by the collision of two such bodies, these nebulæ would represent the second stage in which these existing solid bodies had been converted into a gas of a very high temperature. They would take the same place, if we assume with Sir William Thomson ‡ the coming together of two or more cool solid masses by the velocity due to their mutual gravitation alone.

I pointed out in 1864 § that the gaseous nature of these bodies would afford an explanation of the appearance of flat disks without condensation which many of them present. The light emitted by the portions of the gas farther from us would be in part or wholly absorbed by the gas through which it would have to pass, in this way giving to us the appearance of a luminous surface only.

In some of these bodies there is also a very faint continuous spectrum, which if we had more light might be found to consist, in great part at least, of closely adjacent bright lines. Such is probably the nature, in part, of the apparently continuous spectrum of the nebula with which this paper deals chiefly, the Great Nebula in Orion.

In other gaseous nebulæ strong condensations are seen, and a stronger "continuous" spectrum. When we come to nebulæ of which the nebula in Andromeda may be taken as representative, the strong bright-line spectrum is absent, and we have what for convenience I called in my original observations of these bodies a "continuous" spectrum, though I was careful to point out that it was probably "crossed by bright or dark lines."

Out of about sixty nebulæ and close clusters observed by me up to 1866,

* "Beobachtungen zu Bothkamp," 1872, p. 59.

‡ *Roy. Instit. Proc.*, vol. xii., pp. 15, 16.

† "Stellar Evolution," 1889.

§ *Phil. Trans.*, 1864, p. 442.

I found a proportion of about one-third, namely, nineteen, to present the spectrum of bright lines.*

The stage of evolution which the nebula in Andromeda represents is no longer a matter of hypothesis. The splendid photograph recently taken by Mr. Roberts † of this nebula shows a planetary system at a somewhat advanced stage of evolution; already several planets have been thrown off, and the central gaseous mass has condensed to a moderate size as compared with the dimensions it must have possessed before any planets had been formed.

[Mr. Maunder permits me to add that he does not consider the measures and estimations of the motions of the nebula taken in 1884 and 1887 of any weight, but he attaches great importance to the direct comparisons of March 1884, which show that the nebula has but very little, if any, sensible motion in the line of sight.—May 16.]

NOTE ON THE PRECEDING PAPER

So far as I know, the groups of fine lines crossing the spectrum of the nebula close about the Trapezium stars, which I recorded for the first time in the preceding paper, have not been confirmed by photographs taken subsequently at other observatories. The negative taken in 1888 was too feeble to allow of such enlargement and subsequent reproduction as to show these faint lines in a print. Even under the measuring microscope very carefully adjusted illumination was required to bring the lines into view.

As it might be suggested that marks in the film had been mistaken for real lines, I thought it desirable to have the independent opinion of some experienced spectroscopists as to their real nature.

In June 1894 Professor Liveing, after a careful examination of the plate taken in 1888, wrote in my Observatory book as follows:

“Observed under low power the photograph of the Great Nebula in Orion. The strongest line, 3727, had very plainly two fainter lines on the less refrangible side, and by varying the light I could see traces of two more on the more refrangible side. Passing to the less refrangible rays, I could see a group of four lines somewhat more refrangible than the strong line H γ , and a fifth line less distinct.”

In the same year Professor Scheiner and Professor Keeler, when on visits to my Observatory, added their testimony that the appearances on the negative were in their opinion to be taken as real lines.

* *Phil. Trans.*, 1866, p. 383. P. 122.

† *Monthly Notices R.A.S.*, vol. lxv., p. 49.—[The diagrams have been made with care, but the positions of the lines must be taken from the tables of wave-lengths.—May 13.]

The same year Dr. Hale visited the Observatory, and examined with great care the negative, which was still in good condition. On his return to America he published in *Astronomy and Astrophysics*, vol. xiii., p. 696, the following note on his observations:—

"During a recent visit to the Tulse Hill Observatory, I had the pleasure of examining, at Dr. Huggins' request, the remarkable photograph of the Orion nebula taken in 1888. The cut in *Proc. Roy. Soc.*, vol. xlvi., p. 60 (P. 171), certainly represents very closely the appearance of the negative, which is in an excellent state of preservation. The pairs of lines on either side of the very strong line at $\lambda 3727$ were easily seen, and most of the lines in the group between 3825 and 3900 were visible, though very faint. The lines at 3959, 3975, 3988, and 3998 were seen without difficulty, but the six lines between 4116 and 4167 were so faint that with the illumination used they were made out with great difficulty in the part of the spectrum due to the nebula. The increase in width and brightness of all the lines in the star spectrum was most striking, and could not have been overlooked by the most careless observer. It is probable that with suitable illumination and more time at my disposal I could have seen all the lines with ease."

The negative is still in sufficiently good condition to allow of most of the fine lines being seen under suitable illumination (1909).

NOTE IN REPLY TO SOME OBSERVATIONS OF PROFESSOR CAMPBELL IN *ASTRONOMY AND ASTROPHYSICS**

(From *Astronomy and Astrophysics*, vol. xiii., p. 568, 1894)

With reference to Professor Campbell's observations of the Orion nebula, it may be well for me to state at once that the photographs taken in 1888—1890 are still in good condition, and fully justify the interpretation we put upon them at the time. (See the preceding note, 1909.)

As Professor Campbell's remarks on the broadening of certain portions of the lines on our plates (*Ibid.*, pp. 398, 393) seem to show that he has not understood correctly the interpretation we put upon this appearance, I may say that the view we took, and still hold, is that this broadening is purely a photographic spreading on account of greater brightness of the line at that place. This greater brightness might be due to more energetic radiation, but is to be attributed more probably to radiation from a larger number of molecules in consequence of a greater depth of the nebula in the line of sight, or of local condensations at these places.

Further, we suspected that the strong photographic line at $\lambda 3727$ may

* Vol. xiii., p. 384.

vary in brightness relatively to the hydrogen lines at different points of the nebula, in a manner similar to the known variation in the visible region of the principal line to the line of hydrogen at F.

In the construction of a spectroscope for taking photographs of the spectra of stars as early as 1876 (*Phil. Trans.*, 1880, p. 670) I reduced the time of exposure by using a short camera with a lens of 6·5 inches focal length and a ratio of nearly 1 to 4. In one of the spectroscopes recently constructed the camera lens has half the focal length only of the lens of the collimator, 12 inches, and an aperture of 2·5 inches. In the other instrument with a longer collimator the camera lens has a focal length of $5\frac{3}{4}$ inches only, and a ratio of $\frac{f}{4}$ nearly (1894).

ON A RE-DETERMINATION OF THE PRINCIPAL LINE IN THE SPECTRUM OF THE NEBULA IN ORION, AND ON THE CHARACTER OF THE LINE

(From *Proc. Roy. Soc.*, vol. xlvi., p. 202, 1890)

WE think it desirable to put on record the results of a re-determination of the position of the principal line in the spectrum of the nebula in Orion, under the more favourable conditions of a higher position of the nebula, and of some improvements in the instrumental arrangements.* The spectroscopes have been furnished with new and sensibly perfect object-glasses by Sir Howard Grubb, and a new bright pointer has been fitted to the spectroscopes by Mr. Hilger, which is illuminated by a small incandescent lamp, of which the brightness is controlled by suitable resistances. In all other respects the instrumental arrangements have remained unaltered. The same spectroscope, giving a dispersion of about four prisms, which was described in my paper of 1872 as Spectroscope B,† and was used in the work on this line contained in my paper of 1874,‡ and also throughout the work of last year, with the exception of one single confirmatory observation with a more powerful spectroscope,§ was employed in the present investigation, and also the same arrangements for the comparison spectrum from burning magnesium.

In my earlier spectroscopic work I pointed out that a possible parallactic

* [In a communication last January to the Royal Society, Professor Lockyer stated that he and his assistants had by different methods and with great dispersion compared directly the chief line in the spectrum of the Nebula in Orion with the band of the magnesium-flame spectrum, and that they had found perfect coincidence between the nebular line and the terminal line of the band. Professor Lockyer also stated that they had always seen the line as a fluting. These statements being in direct contradiction to my early observations and to the conclusions of our paper of last year, the necessity was thrown upon us of going over our work again.—July 4.]

† *Proc. Roy. Soc.*, vol. xx., 1872, p. 382.

‡ *Ibid.*, vol. xxii., 1874, p. 252.

§ *Ibid.*, vol. xlvi., 1889, pp. 50, 51.

error of the comparison spectrum may easily come in when a small reflecting prism is placed in the usual way before one half of the slit; and also the possibility of errors from the unavoidable flexure of the spectroscope or of its attachments to the telescope. In 1872 I adopted the plan of placing "the spark or vacuum-tube within the telescope at a moderate distance from the slit. For this purpose holes were drilled in the telescope-tube, opposite to each other, at a distance of 2 feet 6 inches within the principal focus. Tubes were fixed by screws over these holes, and in these tubes slide suitable holders for carrying electrodes or vacuum-tubes. The final adjustment was tested by the comparison of the bright lines of magnesium and the double line of sodium with the Fraunhofer lines *b* and D in the spectrum of the Moon."*

I have since adopted an arrangement in which, when once adjusted, any sensible parallactic effect from a change of position of the source of light

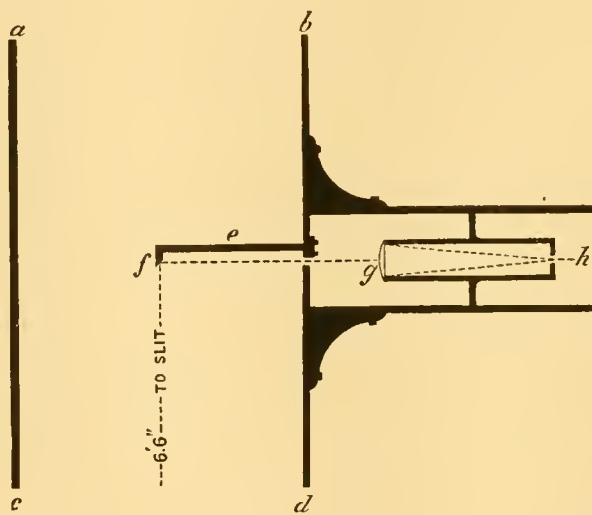


Fig. 24.

seems to be impossible, for even a minute motion of the spark or other source of light for comparison has the effect of throwing the light to one side, without the slit; so that, as long as the comparison spectrum is seen, there can be no doubt that the direction of the light for comparison, as it fell upon the slit, had remained invariably the same, relatively to the optical axis of the telescope, and consequently to the celestial spectrum under observation.

In the diagram, *a b c d* represents a section of the telescope-tube near the middle of its length; within this is firmly screwed a thin steel arm, *e*, carrying a minute mirror, *f*. This mirror is about a quarter of an inch in width, and of about the same apparent length, when seen foreshortened from the slit. The mirror is fixed at a distance of 6 feet 6 inches within the principal focus, where the slit is placed. In the side of the tube opposite the face of the

* *Proc. Roy. Soc., vol. xx., p. 382.*

mirror is a small hole, through which the light from the collimator g passes on to the mirror. At the other end of the collimator, which has a length of about 7 inches, is a diaphragm with a small hole, h , before which the source of light, whether an induction spark, a vacuum-tube, or burning magnesium, is placed. The lens at g is so placed as to bring the light approximately to focus at the place of the slit.

It is obvious that with this arrangement an extremely small shift of the light before the hole h would be sufficient to cause the ray reflected from the mirror to go off the slit, and that the reflected light can pass into the slit only so long as its direction remains sensibly invariable relatively to the optical axis of the telescope. It is also obvious that any flexure in the spectroscope, or in the tube connecting it to the telescope, would affect similarly the light from the nebula and from the magnesium. The precaution was taken, however, to so orient the spectroscope, that any flexure from the weight of the instrument would be in the direction of the length of the slit.

The coincidence or otherwise of the direction of the light reflected from the little mirror with the optical axis of the telescope can be determined by comparing the spectrum of burning magnesium with b in the spectrum of the Moon, or in that of the light of the sky. As an additional safeguard in the comparison of the spectrum of the nebula with magnesium, since my early observations had shown the nebular line to be very slightly more refrangible, the mirror was purposely so adjusted that, though the lines of the burning magnesium were seen to fall upon the corresponding dark lines b in the Moon or sky, yet a careful observation would show a very minute overlapping of the bright lines towards the blue. This state of things would diminish a little the interval which should be seen between the nebular line and the termination of the magnesium-flame band, and so make the observation more difficult. It is evident that if under such circumstances of adjustment the nebular line were seen on the more refrangible side of the magnesia band, the observation, being a delicate one, would be more trustworthy, for in the case of coincidence with magnesium the line would appear towards the opposite and less refrangible side of the magnesium line, broadening the line towards the red (*loc. cit.*, p. 49).

The stability of this adjustment depends upon the rigidity of position of the little mirror within the telescope; as this weighs only a small fraction of an ounce, and is supported by a strong steel arm firmly attached by four screws to the steel tube of the telescope, there is an almost complete absence of any chance of its displacement. During twelve months not the smallest alteration has been detected, though very careful examinations have been frequently made.

At the time the comparisons were made last year, namely, in March, the nebula was getting low, and from perhaps an excess of caution I described

them as follows: "Although I consider the results to be satisfactory, I prefer to say that I and Mrs. Huggins, independently, believed fully at the time that we saw the appearance which all former observations of the line led me to expect, namely, the nebular line to fall within the termination of the magnesium band" (*loc. cit.*, p. 49).

This year the position of the nebular line within the termination of the magnesia band has been confirmed by both of us independently on several nights.

The more refrangible position of the nebular line relatively to the termination lines of the MgO band has been ascertained not only by repeated comparisons of the two spectra by means of a suitably illuminated pointer, but also this year, as last year, by occasional moments of direct vision of the nebular line upon and within the magnesia band. It is only occasionally that the necessary relative brightness of the band can be secured, but such moments of direct vision of the two spectra are very trustworthy.

On February 9, Professor Liveing made some observations on the spectrum of the nebula, and I have his permission to quote from the notes which he entered at the time in my Observatory book. During the afternoon he examined the adjustments of the little mirror. His words are: "Observed in Dr. Huggins' spectroscope attached to his telescope the Fraunhofer lines δ , as given by the clouds, and the bright lines of burning magnesium thrown in by reflection. The solar spectrum was but faint, so that it was necessary to use rather a wide slit. I observed a close coincidence between the dark lines of the sky light and the bright lines of the burning magnesium; the two overlapped, but the dark lines extended a very little on the less refrangible side, the brightest line a very little on the more refrangible side beyond the dark line."

In the evening he observed the nebula, and recorded his observations in the following words: "Observed the spectrum of the nebula in Orion, and compared the position of the least refrangible line with the magnesia fluting. The latter was thrown in by reflection from burning magnesium. I put the nebular line on the pointer first, and then from time to time the magnesium was burnt. I made quite sure that the edge of the magnesia fluting was less refrangible than the nebular line—repeated the observations several times. I tried to see both the nebular line and the fluting at the same time, but found it hard to see both at once; but I still came to the same conclusion, namely, that the edge of the fluting was less refrangible than the nebular line."

Afterwards, Professor Liveing observed the third line of the nebula, together with $H\beta$ from a vacuum-tube. He says: "Compared the position of the most refrangible of the nebular lines with the F line of hydrogen thrown

in by reflection from a vacuum-tube; the coincidence seemed perfect, the one line falling upon the other." *

We have since gone further, and attempted a quantitative estimation of the distance of the nebular line within the termination of the band. For this purpose we made use of the minute apparent breadth of the illuminated pointer-tip as a measuring unit. The value of this unit was determined by measuring with it the distance of b_3 from b_4 in the solar spectrum.

Independent estimations made by both of us on several occasions agreed in assigning to this distance, after taking into account the minute displacement of the comparison-spectrum by the little mirror towards the blue,

A wave-length of about $\lambda 0001\cdot5$

Deducting this distance from $\lambda 5006\cdot5$, the position of the termination of the band, we get for the nebular line

A position of about $\lambda 5005\cdot0$

At the time of these observations the earth's motion caused the nebular line to be degraded towards the red by about $\lambda 0000\cdot25$. If, therefore, the Great Nebula has no motion of its own, this interval must be deducted from the observed position of the nebular line,

Placing it at about $\lambda 5004\cdot75$

The observations recorded in the paper of 1874 † gave the position of the nebular line relatively to the fiducial lead line with an accuracy not less than $\lambda 0000\cdot5$. This relative position was translated into wave-lengths in our paper

* [On April 29, Professor Liveing was kind enough to go over again with us the arrangements for the comparison spectrum, and, in particular, to see if any error could possibly arise from a change of position of the magnesium during its burning. After a detailed account of the experiments, he wrote in my note-book: "I could not detect any shift; and I came to the conclusion that there is no sensible shift due to moving the burning magnesium. I next compared the position of the lead line near the edge of the MgO band, as seen in the same spectroscope detached from the telescope, with the said edge of the band. Both could be seen at the same time, and the apparent distance between them was so great that even if there should be some shift of the lines from the method of throwing in the light when the spectroscope is attached to the telescope, I am satisfied that it could not amount to anything comparable with the distance between the lead line and the edge of the MgO fluting. So far as my memory will serve, the distance from the edge of the MgO fluting at which the nebular line appeared when I observed it on February 9 was not far short of the distance now observed between the lead line and the edge of the MgO fluting."—July 4.]

† *Proc. Roy. Soc.*, vol. xxii., 1874, p. 254. This paper claims for the determination of the position of this line in the case of seven nebulae an accuracy sufficiently great to show a motion of 25 miles per second. This motion corresponds to about $\lambda 0000\cdot67$, but as some of the nebulae were more difficult to observe than the bright nebula in Orion, the accuracy of the determination of the line in this nebula may certainly be taken as not less than the amount given in the text, namely, $\lambda 0000\cdot5$.

on the Nebula (*loc. cit.*, p. 45), showing that the nebular line lies from about $\lambda 5004\cdot 6$ to about $\lambda 5004\cdot 8$.

The question whether this nebula has a motion in the line of sight must be determined by comparisons of the third line with the corresponding bright line of a hydrogen vacuum-tube. The observations I recorded in 1874, as well as those of Mr. Maunder, of Greenwich (*loc. cit.*, p. 60), "show that the nebula has very little, if any, sensible motion in the line of sight."

The direct comparison was made on several nights with results similar to the observation that Professor Liveing recorded on February 9, namely, that "the coincidence seemed perfect, the one line falling upon the other."

We have endeavoured to push this observation further, to determine if the coincidence was absolute, or whether there was a very minute overlapping of the edges of the two lines. The adjustment of the apparatus would throw the hydrogen line, to a very minute extent, towards the blue, at the same time that the earth's motion would degrade the nebular line from the hydrogen line towards the red.

The faintness of the third line with a narrow slit does not permit us to speak with absolute certainty as to the extent which the hydrogen seemed to overlap the nebular line towards the blue.

We were quite certain that the hydrogen line did overlap the nebula slightly towards the blue, but we were unable to determine whether the overlapping corresponded accurately to the earth's motion at the time of observation. It appeared to do so approximately, which would support my former conclusion, that the "nebula has very little, if any, sensible motion in the line of sight."

ON THE CHARACTER OF THE PRINCIPAL LINE IN THE SPECTRUM OF THE NEBULA IN ORION

In our paper last year (*loc. cit.*, p. 53) I stated that "my own observations of this line, since my discovery of it in 1864 . . . show the line to become narrow as the slit is made narrow, and to be sharply and perfectly defined at both edges." We gave also the corroborative evidence of two accurate observers who have made a special study of the spectrum of the gaseous nebulæ, Professor Vogel and Dr. Copeland.

Since last year the defining power of the spectroscopes has been improved by two new object-glasses by Sir Howard Grubb. The nebular line has been subjected on several nights to a very searching examination with different widths of slit; and with different magnifying powers on two spectroscopes—the one with a single prism of 60° , the other the "four-prism" spectroscope (*loc. cit.*, p. 49).

We came to the conclusion that a marked feature of this line is its sharply-defined character on the more refrangible side; we were unable, under any of the conditions of observing, to detect even a suspicion of any softening of the more refrangible edge of the line, much less the faintest indication of a "flare," and certainly not the distinctive peculiarity of a "fluting."

In the case of observations with small dispersion, the eye is helped by placing the second line, which then appears near the first, behind a bar fixed in the eyepiece.

Observations of the nebula in Orion by eye, as well as the photographs of Mr. Common and of Mr. Roberts, show numerous small irregularities in the brightness of the nebula, which give rise to a closely-mottled appearance. As the length of the slit takes in a considerable angular extent of nebula, several of these irregularities of brightness or "mottlings" are usually included within it, giving to the nebular lines an irregularly bright or blotchy appearance. As the nebula is allowed to pass over the slit this blotchy appearance is seen to vary in the size and in the number of the brighter patches, and also in their brightness relatively to the less luminous spaces between them. At the first glance, in some positions of the slit upon the nebula, the lines, and especially the principal line as the brightest, appear almost as if serrated at the edges. A little attention soon shows that this is a purely physiological effect due to the greater brightness of the patches, and that the brighter parts of the line do not really project beyond the less brilliant intervals between them. One marked character of this phenomenon is that both edges of the lines appear equally serrated, and that there is no indication of a spreading of the brighter patches towards the blue only. It is easily ascertained that this more or less patchy condition is not peculiar to the principal line, for precisely the same patches can be detected in the other two lines, and the patches can be seen to correspond in number and in position within the lines.

These observations, repeated on several nights, have left no doubt in our minds that the principal line is certainly as sharp and as bright on the side towards the blue as on the less refrangible side.

On February 9, Professor Liveing scrutinised the character of this line. His words are: "Observed the nebular line with various widths of slit. The line always appeared sharply defined on the more refrangible side, whether the slit were wide or narrow. On gradually closing the slit, the line fined down to a very fine line. The same appearance as to sharpness on the more refrangible side was observable with a spectroscope of less dispersive power and with eyepieces of low power as with the higher dispersion and greater magnification."

The observations recorded in this paper appear to us to show conclusively:—

(1) That the principal line is not coincident with, but falls within, the termination of the magnesium-flame band.*

(2) That in the nebula of Orion this line presents no appearance of being a "fluting."

It is scarcely needful to say that, in the face of the observations recorded in this paper, we are not able to accept the conclusions arrived at by Professor Lockyer in his recent communications † to the Royal Society. From them it would appear that Professor Lockyer confirms my statement made in 1874 ‡ that the second line "is sensibly coincident with an iron wave-length 4957" (Thalén, λ 4956·8; Liveing and Dewar, λ 4956·9); and also that Professor Lockyer's photographs confirm my photographs of 1882, 1888, and 1889, in that it is a single strong line, and not a triplet, which appears in the ultra-violet region, and that this strong line is more refrangible than the first component of the magnesic oxide triplet. §

ADDENDUM. Received June 6, 1890

I. ADDENDUM ON THE POSITION OF THE LINE

One of the planetary nebulae, in the spectra of which I found in my earlier comparisons with lead || in 1874, that the principal line had sensibly the same position as the corresponding line in the nebula of Orion, was Σ. 5 (G. C. 4234). We have now compared again the principal line in this nebula with the lead line λ 5004·5 with the same spectroscope (spectroscope B, 3rd eyepiece) and an arrangement for the comparison spectrum similar to that described in the first part of this paper, but in which the small mirror has been replaced by a very small total reflecting prism. The correctness of position of the comparison spectrum was ascertained by repeated comparisons of the bright lines of magnesium at b with the corresponding dark lines in the Sun's light reflected from the sky.

* [Even if the nebular line appeared to be sensibly coincident under the amount of dispersion which can be brought to bear upon the nebulae, for reasons stated in our paper of last year (*loc. cit.*, p. 55, footnote), the evidence would be strongly in favour of the view that the coincidence was apparent only, and against the assumption that the nebular line was to be regarded as the "remnant" of the magnesium-flame band. We did not, however, give sufficient prominence to the fact of the great brilliancy of the line in many nebulae, without the faintest traces of the second and third flutings. The relative intensities of the brightest ends of these flutings are:—

1st fluting	8
2nd „	7
3rd „	5

(Watts, "Index of Spectra," p. 175). However, the position of the nebular line at a measurable distance from the terminal line of the magnesium-flame band towards the blue makes such considerations superfluous, and disposes finally of the assertion that the nebular line is the "remnant" of the magnesium fluting.—July 4.]

† *Proc. Roy. Soc.*, vol. xlvi., pp. 129 and 189, etc.

§ *Ibid.*, vol. xlvi., p. 54.

‡ *Ibid.*, vol. xxii., p. 252.

|| *Ibid.*, vol. xxii., 1874, p. 254.

When in this spectroscope the spectrum of lead is observed together with that of burning magnesium, the lead line is seen to fall well within, and to be separated by a clear space from, the terminal line of the magnesium-flame fluting.

The principal line of $\Sigma. 5$, like that of the nebula of Orion, appears when the slit is made narrow to be very thin and clearly defined at both edges. The lead line is a thin and defined line; if, therefore, the nebular line were coincident with the terminal line of the magnesium-flame fluting, it would appear in the spectroscope to be separated by a clear space from the lead line towards the red. As the angular diameter of the nebula is small, the line is much shorter than the lead line—not longer than about one-third of the height of the spectrum, and consequently its position relatively to the lead line, even when it falls partly upon it, can be very accurately determined.

The nebular line was seen as a short thin bright line partly upon, and partly clinging to, the lead line. The nebular line in our instrument certainly fell upon the lead line, but overlapped it a very little, though not so much as by half its breadth, on the less refrangible side. This position agrees precisely with that described in my early observations made nearly twenty years ago, when I employed for the first time lead as a fiducial comparison line.* As I stated in 1874,† “if greater prism power could be brought to bear upon the nebulae, the line in the lead spectrum would be found to be in a small degree more refrangible than the line in the nebula;” and, of course, if sufficient power of dispersion were employed, the nebular line would be seen separated from the lead line towards the red, and not, as in our instrument, partly upon the lead line.

These observations, both those by myself in 1874 and the recent observations made by both of us independently on four different nights, place the nebular line exactly where it was found to be by our direct comparisons with burning magnesium in the nebula of Orion (which were confirmed by Professor Liveing), namely, as not coincident with, but as falling well within, the terminal line of the magnesium-flame spectrum.

It should be stated that on two nights we made comparisons of $\Sigma. 5$ with burning magnesium, both directly, and indirectly by means of the illuminated pointer. The observations completely confirmed the results of the lead comparisons, which were, however, more easily made, as it is difficult to see the exact position of the short nebular line when it is upon the bright fluting.‡

* *Proc. Roy. Soc.*, vol. xxii., p. 252.

† *Ibid.*

‡ [On one night, as had been frequently done when we were observing the nebula in Orion, after the comparison of the nebula with lead and magnesium had been made, the spectroscope was left attached to the telescope in order that we might verify the correctness of position of the comparison spectrum by means of the light of sky on the following day, without any change whatever having taken place in the adjustments of the instrument. The result of this verification was, as always when working on Orion, absolutely satisfactory.—July 4.]

2. ADDENDUM ON THE CHARACTER OF THE LINE

I am permitted by Dr. Copeland, Professor Young, and Mr. Keeler, of the Lick Observatory, to quote the following observations, which they have been so kind as to make at my request, of the character of the principal line in the spectrum of the Great Nebula in Orion.

Dr. Copeland writes, dated March 26, 1890: "I find it difficult to make anything satisfactory of nebular spectra with my present apparatus, working in the smoke of Edinburgh. . . . On the 14th I saw the three lines as well as I am likely to see them until we get to work at the new observatory. All the lines were just as broad as the slit; when the slit was wide open they were broad, and when the slit was closed slowly they gradually became narrower and narrower."

Professor Young, writing on March 21, 1890, says: "I have not been able this winter to try the observations for wave-length, having no convenience for the comparison spectrum, but I have carefully examined the spectrum of the nebula of Orion, both with a heavy glass prism, and with a grating of 14,000 to the inch, and a collimator of 16 inches focus. With the prism the brightest nebular line seemed absolutely *sharp*, and cleanly defined on both sides; with the grating the line was fainter, and I could not use so narrow a slit; the dispersion was much higher also; the line therefore was a little hazy, *but equally so on both sides.*"

At the Lick Observatory there was a continuance of bad weather during the early months of the year, but Mr. Keeler, with Dr. Holden's kind permission, observed the nebula on two nights. He observed successively with one prism, a powerful compound prism, and then with a Rowland grating, 14,000 lines to the inch. With this grating, the collimator was 20 inches in length, the observing telescope $10\frac{1}{2}$ inches, with an eyepiece magnifying 13.3 times. The slit was narrow—0.0025 inch. The spectra up to the fourth order were employed.

Mr. Keeler says: "One thing that struck me particularly, and that there could be no doubt of, was the perfect sharpness and fineness of the nebular lines under the very considerable dispersion used. There is not the least doubt in my mind that they are all of gaseous origin—not 'remnants of flutings.'"

[The observations with large dispersion by Professor Young, and especially those of Mr. Keeler, after observing with one prism, and then with a compound prism, that the line remained sharp even when examined in the 4th Spectrum of a grating 14,000 + to the inch, are of great value in regard to Mr. Maunder's observations. It was on one occasion only, when he made use of the very great dispersion of 80° from A to H, equal to about sixteen prisms of 60° , that he observed the nebular line to be otherwise than sharp and defined. On this unique occasion he says: "The three lines were seen

as narrow bright lines, but none of them were perfectly sharp ; each showed a slight raggedness at both edges, but in the case of the line near λ 5005 it was clear that this fringe or raggedness was developed towards the blue." Mr. Maunder significantly adds : " In the case of the other two lines they were not bright enough for it to be possible to ascertain whether the fringes were symmetrical or not."* The new observations at Princeton and at the Lick Observatory would seem to leave little doubt that if the other lines had been as bright as the principal line, the raggedness about them would have been found to be equally unsymmetrical, and that the want of symmetry affected all three lines, and was probably instrumental.—July 4.]

SECOND ADDENDUM. Received July 4

ON THE POSITION OF THE LINE

On account of the unusual weather at the Lick Observatory during the early part of this year, Dr. Holden informs me that " The observing chances have been amazingly small." For this reason, although, in addition to the observations on the character of the chief line in the nebula of Orion, measurements of its position were attempted on two nights, the interruption from clouds was so constant that they could not be satisfactorily completed.

Under these circumstances, I asked Dr. Holden to have the kindness to telegraph to me if Mr. Keeler should be able to confirm the position of the line as not coincident with the magnesium-fluting in the nebula Σ . 5.

On June 15th I received a telegram with the words : " Confirmed Struve. 5. Keeler."

I have received since a letter from Mr. Keeler, dated June 14th, 1890, in which he says : " Last night I compared the brightest line in the spectrum of Σ . 5 with the magnesium fluting of nearly the same wave-length, and I am glad to say that my observations were in accordance with your own." . . . " On comparing the brightest line with the magnesium fluting, both directly and by aid of the micrometer wire, the line was seen to be well within the limits of the fluting, and separated by a small but unmistakable interval from its bright lower edge. The appearance was the same on both sides of the grating, and in the 3rd and 4th spectra. The comparison apparatus was carefully adjusted, and no shifting of the line was caused by changing the position of the spark. The edge of the fluting *could not* be brought into coincidence with the nebular line. No measurement of the difference of wave-length was made, as my attention was directed to the main fact of the non-coincidence of the line in all positions of the instrument. I will make such measures as soon as possible."

* *Monthly Notices R.A.S.*, vol. xlix., 1889, p. 308.

(Summary of Professor Keeler's later observations on the bright lines of the nebulæ: "There is no evidence in the visible spectrum of the presence of magnesium in the nebulae."

Normal position of the chief nebular line is λ 5007·05, Rowland's scale. Position of the second nebular line, λ 4959·02.

"The spectrum of the bright-line nebulæ indicates either a high temperature of the gases emitting the light, or a state of strong electrical excitement, and shows that the temperature and pressure are greatly increased at the nucleus." (Publications of the Lick Observatory, vol. iii., p. 165, 1894.) [1909.]

NOTE ON THE PHOTOGRAPHIC SPECTRUM OF THE GREAT NEBULA IN ORION

(From *Proc. Roy. Soc.*, vol. xlviii., p. 213, 1890)

FROM an examination of the photographs of the spectrum of the nebula in Orion taken by us in 1882, 1888, and 1889, we suggested in our paper "On the Spectrum, Visible and Photographic, of the Great Nebula in Orion,"* "that the mottled and broken-up character of the nebular matter shown in Lord Rosse's drawings from eye-observations, and much more strikingly brought out in the recent photographs of Mr. Common and of Mr. Roberts, may be connected with differences of spectrum in the photographic region, though in the visible region there is no known alteration of the spectrum of the four bright lines, except it may be some small differences of relative brilliancy of the lines. Until next winter we cannot go beyond the new information which these photographs give to us."

Unfortunately, the necessity thrown upon us of making a laborious redetermination of the position and character of the principal line in the visible spectrum,† which has confirmed in every point the results contained in our paper of last year (*loc. cit.*), has deprived us of the more favourable opportunities during the past season of carrying out our intention of photographing the spectra of different parts of the nebula.

We have obtained two photographs only, one taken on March 14 and 15, and the other on March 17; but these suggest how much information a spectroscopic examination by photography of the nebula in detail would probably give to us.

These photographs, taken of almost the same part of the nebula as the photograph of 1889, showed, to our surprise, the lines of hydrogen at $\text{H}\alpha$ and at $\text{H}\beta$ strongly impressed upon the plate, though these lines were carefully searched for in vain in our former photographs; in them no trace of these

* *Proc. Roy. Soc.*, vol. xlvi., p. 42.

† *Ibid.*, vol. xlvii., pp. 129 and 189, etc.

lines could be detected, but the line near G was strong, and there was present a large number of faint lines, of about thirty of which the approximate measures were given in our paper.

The new photographs show not only the lines of hydrogen at λ and H, but also the first two lines of the ultra-violet series in the white stars which I described in 1879.* Four of these lines had been photographed in the spectrum of hydrogen by Dr. H. W. Vogel, in 1879, and the entire series, with the exception of one, has been since obtained by Cornu in exceptionally pure hydrogen.†

The line ζ at λ 3887·8 is strong, and the next line η at λ 3834·5, though much fainter, is certainly present. There is evidence of light-action on the plate at the position of the line θ which we believe to be present; and we suspect, from traces of photographic action, that one or more of the other lines of the white star series might have come out with a longer exposure.

It is not necessary to point out in the present note the importance of the presence of these more refrangible lines of hydrogen in respect of the view we have to take of the condition of things in the nebula. In this connection it is significant that the hydrogen lines are sensibly stronger and broader on the plate as the Trapezium with its stars is approached.

Between the hydrogen lines ζ and η there is a line stronger even than ζ , which has a wave-length of about λ 3868.

We do not find any line in the photograph exactly at the place of the solar line K; the position of this line appears to correspond to a gap between two lines on the plate. We suspect the broad line on the less refrangible side of the place of K would probably be resolved by a narrower slit into two or more lines.

The strong line which was first seen in our photograph of the nebula taken in 1882 is certainly stronger than H θ , and is by far the most powerful line in the photographic region. On account of the wide slit employed in my original photograph, I put the line at about λ 3730; from measures of the line in a photograph, taken in 1889, with a narrower slit, we found that its position was more refrangible, and we gave the approximate wave-length "about λ 3724." There was necessarily some difficulty in determining its position exactly on account of the small scale on which, from the faintness of the light of the nebula, it is desirable with the telescope at our disposal to take the photographs, and also because in the nebular spectrum itself we had no fiducial line nearer than H θ . In the photographs taken this year we have the advantage of the known position of the hydrogen line at H, and with the help of this line our recent measures show that the "about" must be interpreted as slightly less refrangible than λ 3724. Without attempting to fix its

* *Phil. Trans.*, 1880, p. 669.

† *Journal de Physique*, 2nd ser., vol. vi., August 1886.

position absolutely, we believe that the line will be found to fall between $\lambda 3725$ and $\lambda 3726$. It is not needful to point out that measures of these little photographs cannot compare in accuracy with direct comparisons with considerable dispersion, as in the case of our observations of the chief line of the nebula by eye. It is, however, now certain that the line does not coincide with any one of the three components of the magnesic oxide triplet, but is less refrangible than the middle line at $\lambda 3724$, and falls between this line and the first line of the triplet at $\lambda 3730$.

In these photographs there is a strong line, besides many faint lines, on the less refrangible side of G.

The background of the spectrum is seen to contain numerous faint lines, which, as far as we have been able to identify them, are the same as those seen in our earlier photographs, of some of which approximate measures were given in our paper; but they are, possibly on account of a slightly wider slit, not so easily measured as they were in the former photographs, in which no traces of the hydrogen lines at $H\alpha$ and at H could be detected.

A marked feature of the lines consists of their abruptly different intensities at different parts of their length, giving the blotchy appearance which is characteristic of the lines in the visible spectrum, and which we have described in our recent paper "On a Re-determination of the Position and Character of the Principal Line in the Spectrum of the Nebula in Orion." The length of the slit takes in a large angular extent of the nebula, and, therefore, usually includes within it one or more of the brighter "mottlings" which are so well shown in photographs of the nebula. It is to be remarked that these brighter blotches are sharply bounded, showing that the different parts of the nebula are to some extent distinct and often become suddenly brighter than the neighbouring parts.

The lines of the new photographs contain two very strong and abruptly-bounded blotches, and a third one less marked.

These brighter blotches, corresponding to different conditions of closely-adjacent nebular matter, give an explanation of an appearance which we recorded last year in speaking of the strong line "about $\lambda 3724$." "On one side of the star-spectra this line is a little broader than on the other side; but, as a similar appearance is presented by $H\gamma$ and the stronger lines of the group, it may arise from some optical or photographic cause."

We now learn that this difference between two parts of the lines indicates probably a different condition of the nebula on the two sides of the star-spectra.

Other lines besides those described in this note are present, not only between G and F, but also on the more refrangible side of the strong line about $\lambda 3725$.

The importance of the new points which have come out from these photographs makes us regret that we must postpone a fuller examination and discussion of the spectrum of different parts of the nebula until its return next year.

(My later measures gave $\lambda 3726$ for the brilliant ultra-violet line, which reduced to Rowland's scale becomes $\lambda 3726\cdot5$. Since that time the line has been measured by Keeler and by Campbell.

Huggins, Rowland's scale	$\lambda 3726\cdot5$
Keeler , " , " , " , "	$3726\cdot5$
Campbell , " , " , " , "	3727

"Considering the small scale on which the spectrum is reproduced in the present volume, we considered it would be convenient to avoid decimals, and to take the wave-length at $\lambda 3727$." (*Atlas of some Representative Stellar Spectra*, Wesley, 1899, p. 138.) [1909.]

(We repeat here the reproduction of the photograph taken on March 17, 1890, which appeared on Plate III. of the *Atlas*, as it contains several original points of interest which have been described in the preceding paper, and are the subjects of further discussion in the *Atlas*, p. 134. 1909.)

SUN & GREAT NEBULA in ORION

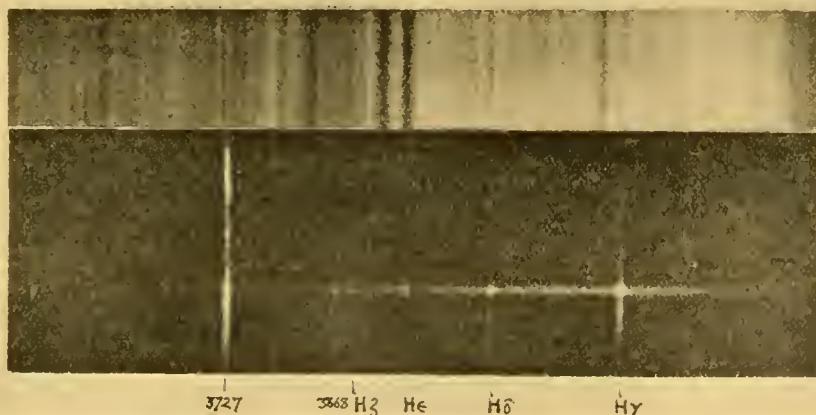


Fig. 25.

NOTE ON THE SPECTRUM OF THE GREAT NEBULA IN ANDROMEDA.
(Added May 1909.)

In the *Bulletin of the Lick Observatory*, No. 149, March 1909, Mr. Fath reproduces some photographs of Spiral Nebulæ and Stellar Clusters, taken with the Crossley Reflector. His photographs show the spectrum of the Great Nebula

in Andromeda as a solar one. It seems desirable now to give a few sentences from the *Atlas* on the early work done here on the spectrum of this nebula.

"The first application of the spectroscope to the light of the Great Nebula in Andromeda was made by me in 1864. . . . I record that: 'The spectrum could be traced from about D to F. The light appeared to cease very abruptly in the orange. This may be due to the smaller luminosity in this part of the spectrum. No indication of bright lines.'

"We include among the Historical Spectra (Plate II.) a reproduction of a photograph of this nebula taken here in 1888, with an exposure of about four hours. Two solar spectra, one above and the other below, were taken for the purpose of comparison. In the negative, crossing the extremely faint action due to the nebular light, are to be seen several dark lines, among them a pair of dark lines at K and H, and a line or lines about the position of the solar G.

"A faint trace of similar dark lines can be just detected across the faint action on the plate of the brightest part of the Dumb-bell Nebula, which had two exposures, making together three hours, on November 12 and 15, 1889.

"We did not publish at the time an account of the photographs of the Nebula in Andromeda taken here in 1888, as we were uncertain whether the dark lines were due to the nebula itself, or to some faint traces of solar light, though the nights on which they were taken were free from moonlight."

Eleven years later, Scheiner published an account of a photograph of the Nebula in Andromeda which showed lines agreeing in position with some of the stronger lines of the solar spectra. (*Ast. Nach.*, B. 148, s. 325, 1899.)

"In the Cassegrain Reflector, as now arranged for photographic spectroscopy, the light suffers reflection from both specula, and the conjugate focal length is a very long one—conditions very unfavourable for photographing the spectra of celestial bodies of sensible size; nevertheless we exposed a plate for ten hours spread over several nights, on the chance that possibly the ultra-violet radiation of the nebula might be strong relatively to that in the visual region. The accumulated action of the light of the nebula during the ten hours upon the sensitive film was a very feeble one, if indeed the plate can be said to have been impressed to a sensible extent."

On this account we devoted a large amount of time and labour, during several years, to an examination by eye of the spectra of this and of other nebulae and clusters.

"On the night of October 8, 1890, we were rewarded with unmistakable views of the red end of the spectrum of this nebula as far as C."

Observations of the true character of the extremely feeble continuous spectrum were of great difficulty. "The final conclusion from the long series of eye observations was that the continuous spectrum of the nebula—that is, of its brightest, central part—contains dark lines of absorption, and also some bright lines." (*Atlas*, pp. 119–26.)

Section IV
MOTION IN THE LINE OF SIGHT

LIST OF PAPERS

- “Further Observations on the Spectra of some of the Stars and Nebulæ, with an Attempt to Determine therefrom whether these Bodies are Moving towards or from the Earth; also Observations on the Spectra of the Sun and of Comet II, 1868.”
Phil. Trans., 1868, vol. clviii., p. 529. P. 197.
- “On the Spectrum of the Great Nebula in Orion; and on the Motions of Stars towards and from the Earth.”
Proc. Roy. Soc., vol. xx., p. 379, 1872. P. 216.
- “Note on the Proper Motions of the Nebulæ.”
Report Brit. Assoc., 1873, p. 34.
- “On the Motions of some of the Nebulæ towards or from the Earth.”
Proc. Roy. Soc., vol. xxii., p. 251 (No. 151, 1874). P. 224.
- “Letter in reply to Father Secchi on the Displacement of the Stellar Lines.”
Phil. Mag., July 1876. P. 227.
- “The Spectroscopic Method of Determining Motion in the Line of Sight.”
The Observatory, December 1901, and *Astrophysical Journal*, vol. xiv., p. 369. P. 230.

HISTORICAL STATEMENT

(From the *Nineteenth Century Review*, June 1897)

FROM the beginning of our work upon the spectra of the stars, I saw in vision the application of the new knowledge to the creation of a great method of astronomical observation which could not fail in future to have a powerful influence on the progress of astronomy ; indeed, in some respects greater than the more direct one of the investigation of the chemical nature and the relative physical conditions of the stars.

It was the opprobrium of the older astronomy—though indeed one which involved no disgrace, for *à l'impossible nul n'est tenu*—that only that part of the motions of the stars which is across the line of sight could be seen and directly measured. The direct observation of the other component in the line of sight, since it caused no change of place and, from the great distance of the stars, no appreciable change of size or of brightness within an observer's lifetime, seemed to lie hopelessly quite outside the limits of man's powers. Still, it was only too clear that, so long as we were unable to ascertain directly those components of the stars' motions which lie in the line of sight, the speed and direction of the solar motion in space, and many of the great problems of the constitution of the heavens, must remain more or less imperfectly known.

Now as the colour of a given kind of light, and the exact position it would take up in a spectrum, depends directly upon the length of the waves, or, to put it differently, upon the number of waves which would pass into the eye in a second of time, it seemed more than probable that motion between the source of the light and the observer must change the apparent length of the waves to him, and the number reaching his eye in a second. To a swimmer striking out from the shore each wave is shorter, and the number he goes through in a given time is greater than would be the case if he had stood still in the water. Such a change of wave-length would transform any given kind of light, so that it would take a new place in the spectrum, and from the amount of this change to a higher or to a lower place, we could determine the velocity per second of the relative motion between the star and the earth.

The notion that the propagation of light is not instantaneous, though rapid far beyond the appreciation of our senses, is due, not as is sometimes stated to Francis, but to Roger Bacon. "Relinquitur ergo," he says, in his *Opus Majus*, "quod lux multiplicatur in tempore . . . sed tamen non in tempore sensibili et perceptibili a visu, sed insensibili. . . ."

The discovery of its actual velocity was made by Roemer in 1675, from observations of the satellites of Jupiter. Now, though the effect of motion in the line of sight upon the apparent velocity of light underlies Roemer's determinations, the idea of a change of colour in light from motion between the source of light and the observer was announced for the first time by Doppler in 1841. Later, various experiments were made in connection with this view by Ballot, Sestini, Klinkerfues, Clerk Maxwell, and Fizeau. But no attempts had been made, nor were indeed possible, to discover by this principle the motions of the heavenly bodies in the line of sight. For, to learn whether any change in the light had taken place from motion in the line of sight, it was clearly necessary to know the original wave-length of the light before it left the star.

As soon as our observations had shown that certain earthly substances were present in the stars, the original wave-lengths of their lines became known, and any small want of coincidence of the stellar lines with the same lines produced upon the earth might safely be interpreted as revealing the velocity of approach or of recession between the star and the earth.

These considerations were present to my mind from the first, and helped me to bear up under many toilsome disappointments: "Studio fallente labore." It was not until 1866 that I found time to construct a spectroscope of greater power for this research. It would be scarcely possible, even with greater space, to convey to the reader any true conception of the difficulties which presented themselves in this work, from various instrumental causes, and of the extreme care and caution which were needful to distinguish spurious instrumental shifts of a line from a true shift due to the star's motion.

At last, in 1868, I felt able to announce, in a paper printed in the *Transactions of the Royal Society* for that year, the foundation of this new method of research, which, transcending the wildest dreams of an earlier time, enables the astronomer to measure off directly in terrestrial units the invisible motions in the line of sight of the heavenly bodies.

To pure astronomers the method came before its time, since they were then unfamiliar with Spectrum Analysis, which lay completely outside the routine work of an observatory. It would be easy to mention the names of men well known, to whom I was "as a very lovely song of one that hath a pleasant voice." They heard my words, but for a time were very slow to avail themselves of this new power of research. My observations were, how-

ever, shortly afterwards confirmed by Vogel in Germany; and by others the principle was soon applied to solar phenomena. By making use of improved methods of photography, Vogel has recently determined the motions of approach and of recession of some fifty stars, with an accuracy of about an English mile a second. In the hands of Young, Dunér, Keeler, and others, the method has been successfully applied to a determination of the rotation of the sun, of Saturn and his rings, and of Jupiter.

It has become fruitful in another direction, for it puts into our hands the power of separating double stars which are beyond the resolving power of any telescope that can ever be constructed. Pickering and Vogel have independently discovered by this method an entirely new class of double stars.

Double stars too close to be separately visible unite in giving a compound spectrum. Now, if the stars are in motion about a common centre of gravity, the lines of one star will shift periodically relatively to similar lines of the other star, in the spectrum common to both; and such lines will consequently, at those times, appear double. Even if one of the stars is too dark to give a spectrum which can be seen upon that of the other star, as is actually the case with Algol and Spica, the whirling of the stars about each other may be discovered from the periodical shifting of the lines of the brighter star relatively to terrestrial lines of the same substance. It is clear that as the stars revolve about their common centre of gravity, the bright star would be sometimes advancing, and at others receding, relatively to an observer on the earth, except it should so happen that the stars' orbit were perpendicular to the line of sight.

It would be scarcely possible, without the appearance of great exaggeration, to attempt to sketch out even in broad outline the many glorious achievements which doubtless lie before this method of research in the future.

FURTHER OBSERVATIONS ON THE SPECTRA OF SOME OF THE STARS AND NEBULÆ, WITH AN ATTEMPT TO DETERMINE THEREFROM WHETHER THESE BODIES ARE MOVING TOWARDS OR FROM THE EARTH

(From *Phil. Trans.*, vol. clviii., p. 529, 1868)

INTRODUCTION

In a paper "On the Spectra of some of the Fixed Stars" * by myself and Dr. W. A. Miller, Treas. R.S., we gave an account of the method by which we had succeeded during the years 1862 and 1863 in making trustworthy

* *Phil. Trans.*, 1864, p. 413.

simultaneous comparisons of the bright lines of terrestrial substances with the dark lines in the spectra of some of the fixed stars. We were at the time fully aware that these direct comparisons were not only of value for the more immediate purpose for which they had been undertaken, namely, to obtain information of the chemical constitution of the investing atmospheres of the stars, but that they might also possibly serve to tell us something of the motions of the stars relatively to our system. If the stars were moving towards or from the earth, their motion, compounded with the earth's motion, would alter to an observer on the earth the refrangibility of the light emitted by them, and consequently the lines of terrestrial substances would no longer coincide in position in the spectrum with the dark lines produced by the absorption of the vapours of the same substances existing in the stars.

The apparatus employed by us was furnished with two prisms of dense flint glass, each with a refracting angle of 60° , and permitted the comparisons to be made with so much accuracy that the displacement of a line, or of a group of lines, to an amount smaller even than the interval which separates the components of Fraunhofer's D would have been easily detected. We were, therefore, in possession of the information that none of the stars the lines in the spectra of which we had compared with sufficient care, were moving in the direction of the visual ray with a velocity so great, relatively to that of light, as to shift a line through an interval corresponding to a difference of wavelength equal to that which separates the components of D. To produce an alteration of refrangibility of this amount, a velocity of about 196 miles per second would be required. The following stars, with some others, were observed with the requisite accuracy: Aldebaran, α Orionis, β Pegasi, Sirius, α Lyrae, Capella, Arcturus, Pollux, Castor.

It appeared premature at the time to refer to these negative results, as it did not seem to be probable that the stars were moving with velocities sufficiently great to cause a change of refrangibility which could be detected with our instrument. The insufficiency of our apparatus for this very delicate investigation does not, however, diminish the trustworthiness of the results we obtained respecting the chemical constitution of the stars, as the evidence for the existence or otherwise of a terrestrial substance was made to rest upon the coincidence, or want of coincidence, in general character as well as position of *several lines*, and not upon that of a single line.

According to the undulatory theory, light is propagated with equal velocity in all directions, whether the luminous body be at rest or in motion. The change of refrangibility is therefore to be looked for from the diminished or increased distance the light would have to traverse if the luminous object and the observer had a rapid motion towards or from each other. The great relative velocity of light to the known planetary velocities, and to the probable

motions of the few stars of which the parallax is known, showed that any alterations of position which might be expected from this cause in the lines of the stellar spectra would not exceed a fraction of the interval between the double line D, for that part of the spectrum.

I have devoted much time to the construction and trial of various forms of apparatus, with which I hoped to accomplish the detection of so small an amount of refrangibility. The difficulties of this investigation I have found to be very great, and it is only after some years that I have succeeded in obtaining a few results which I hope will be acceptable to the Royal Society.

The subject of the influence of the motions of the heavenly bodies on the index of refraction of light had already, at the time of the publication of our paper in 1864, occupied the attention of Mr. J. C. Maxwell, F.R.S., who had made some experiments in an analogous direction. In the spring of last year, at my request, Mr. Maxwell sent to me a statement of his views and of the experiments which he had made. I have his permission to enrich this communication with the clear statement of the subject which is contained in his letter, dated June 10, 1867.

In 1841, Doppler showed that since the impression which is received by the eye or the ear does not depend upon the intrinsic strength and period of the waves of light and of sound, but is determined by the interval of time in which they fall upon the organ of the observer, it follows that the colour and intensity of an impression of light, and the pitch and strength of a sound will be altered by a motion of the source of the light or of the sound, or by a motion of the observer, towards or from each other.*

Doppler endeavoured by this consideration to account for the remarkable differences of colour which some of the binary stars present, and for some other phenomena of the heavenly bodies. That Doppler was not correct in making this application of his theory is obvious from the consideration that even if a star could be conceived to be moving with a velocity sufficient to alter its colour sensibly to the eye, still no change of colour would be perceived, for the reason that beyond the visible spectrum, at both extremities, there exists a store of invisible waves which would be at the same time exalted or degraded into visibility, to take the place of the waves which had been raised or lowered in refrangibility by the star's motion. No change of colour, therefore, could take place until the whole of those invisible waves of force had been expended, which would only be the case when the relative motion of the source of light and the observer was several times greater than that of light.

In 1845, Ballot published a series of acoustic experiments which support Doppler's theory in the case of sound. In the same paper Ballot advances

* "Ueber das farbige Licht der Doppelsterne und einiger anderer Gestirne des Himmels."—Böhm. Gesell. Abh. ii. 1841-42, S. 465.

several objections to Doppler's application of his theory to the colours of the stars.*

This paper was followed by several papers by Doppler in reply to the objections which were brought against his conclusions.†

In 1847 two memoirs were published by Sestini on the colours of the stars in connection with Doppler's theory.‡

More recently, in 1866, Klinkerfues § published a memoir on the influence of the motion of a source of light upon the refrangibility of its rays, and described therein a series of observations from which he deduces certain amounts of motion, in the case of some of the objects observed by him.

The method employed by Klinkerfues has been critically discussed by Dr. Sohncke.||

It may be sufficient to state that as Klinkerfues employs an achromatic prism, it does not seem possible, by his method of observing, to obtain any information of the motion of the stars; for in such a prism the difference of period of the luminous waves would be, as far as possible, annulled. It is, however, conceivable that his observations of the light when travelling from E. to W., and from W. to E., might show a difference in the two cases, arising from the earth's motion through the ether.

Father Secchi has quite recently called attention to this subject.¶ In his paper he states that he has not been able to detect any change of refrangibility in the case of certain stars, of an amount equal to the difference between the components of the double line D. These results are in accordance with those obtained by myself and Dr. Miller in 1863, so far as they refer to the stars which had been examined by us.

Father Secchi's method of using an unrefracted image as a fiducial mark with diverging rays passing through the prisms might, it is conceivable, be open to objection. He appears to consider that, to produce a certain alteration of refrangibility, half the velocity would be required in the case of the approach of a star to that which would be necessary if the star were receding. This is not the case, for equal velocities of separation or approach give equal changes of wave-length. It is true that a difference of an octave

* "Akustische Versuche auf der Niederländischen Eisenbahn nebst gelegentlichen Bemerkungen zur Theorie des Hrn. Prof. Doppler."—Pogg. Ann. B. lxvi. S. 321.

† See Pogg. Ann. B. lxxxi. S. 270, and Pogg. Ann. B. lxxxvi. S. 371.

‡ "Memoria sopra i colori delle stelle del catalogo de Baily osservati dal P. Band Sestini." Roma, 1847..

§ "Fernere Mittheilungen über den Einfluss der Bewegung der Lichtquelle auf die Brechbarkeit eines Strahls, von W. Klinkerfues."—Nachr. K. G. der W. zu Göttingen, No. 4, S. 33.

|| "Ueber den Einfluss der Bewegung der Lichtquelle auf die Brechung, kritische Bemerkungen zu der Entdeckung des Hrn. Prof. Klinkerfues. Von Hrn. Dr. Sohncke."—Astron. Nachr., No. 1646.

¶ *Comptes rendus*, 2 Mars 1868, p. 398.

is produced by a relative velocity of separation equal to that of light, and by a velocity of approach equal to half that of light; but the difference in length of a wave and its octave below (which is twice as long) is in the same proportion greater than the difference between it and the octave above (which is half as long).

The experiments of M. Fizeau in connection with this subject are referred to by Mr. Maxwell in the following statement of his views and experiments, which was received by me on June 12, 1867.

ON THE INFLUENCE OF THE MOTIONS OF THE HEAVENLY BODIES ON THE INDEX OF REFRACTION OF LIGHT

Let a source of light be such that it produces n disturbances or vibrations per second, and let it be at such a distance from the earth that the light requires a time T to reach the earth. Let the distance of the source of light from the earth be altered, either by the motion of the source of light or by that of the earth, so that the light which emanates from the source t seconds afterwards reaches the earth in a time T' .

During the t seconds nt vibrations of the source of light took place, and these reached the earth between the time T and the time $t + T'$, that is, during $t + T' - T$ seconds. The number of vibrations which reached the earth per second was therefore no longer n , but $n \frac{t}{t + T' - T}$.

If v is the velocity of separation of the source of light from the earth, and V the velocity of light between the bodies relative to the earth, then $vt = V(T' - T)$, and the number of vibrations per second at the earth will be $n \frac{V}{V + v}$.

If V_0 is the velocity of propagation of light in the luminiferous medium, and if v_0 is the velocity of the earth,

$$V = V_0 - v_0,$$

and the wave-length will be increased by a fraction of itself equal to

$$\frac{v}{V_0 - v_0}.$$

Since v_0 only introduces a correction which is small compared even with the alteration of wave-length, it cannot be determined by spectroscopic observations with our present instruments, and it need not be considered in the discussion of our observations.

If, therefore, the light of the star is due to the combustion of sodium, or any other element which gives rise to vibrations of definite period, or if the light of the star is absorbed by sodium vapour, so as to be deficient in vibrations of a definite period, then the light, when it reaches the earth, will have an excess or defect of rays whose period of vibration is to that of the sodium period as $V + v$ is to V .

As an example, let us suppose the star to be fixed and the earth to be moving directly away from the star with the velocity due to its motion round the sun. The coefficient of aberration indicates that the velocity of light is about 10,000 times that of the earth in its orbit, and it appears from the observations of Ångström and Ditscheiner that the wave-length of the less refrangible of the lines forming D exceeds that of the other by about one-thousandth part of itself. Hence, if the lines corresponding to D in the light of the star are due to sodium in the star, these lines in the starlight will be less refrangible than the corresponding lines in a terrestrial sodium-flame by about a tenth part of the difference between D_1 and D_2 .

When the earth is moving towards the star, the lines will be more refrangible than the corresponding terrestrial lines by about the same quantity.

The effect of the proper motion of stars would of course have to be compounded with the effect of the earth's own motion, in order to determine the velocity of approach or separation.

To observe these differences of the light from stars, a *spectroscope* is necessary, that is, an instrument for separating the rays of different periods; and it is immaterial in what direction the refraction of the light through the prisms takes place, because the *period* of the light is the thing to be observed by comparison with that of a terrestrial flame.

If, instead of a spectroscope, an achromatic prism were used, which produces an equal deviation on rays of different periods, no difference between the light of different stars could be detected, as the only difference which could exist is that of their period.

If the motion of a luminiferous medium in the place where the experiment is made is different from that of the earth, a difference in the deviation might be expected according to the *direction* of the ray within the prisms, and this difference would be nearly the same whatever the source of the light.

There are therefore two different and independent subjects of experiment. The one is the alteration in the period of vibration of light due to the relative motion of the stars and the earth. The fact of such an alteration is independent of the form under which we accept the theory of undulations, and the possibility of establishing its existence depends on the discovery of lines in the stellar spectra, indicating by their arrangement that their origin is due to the existence of substances in the star having the same properties as substances found on

the earth. Any method of observing small differences in the period of vibration of rays, if sufficiently exact, will enable us to verify the theory, and to determine the actual rate of approach or separation between the earth and any star.

The other subject of experiment is the relation between the index of refraction of a ray and the direction in which it traverses the prism. The essentials of this experiment are entirely terrestrial, and independent of the source of light, and depend only on the relative motion of the prism and the luminiferous medium, and on the direction in which the ray passes through the prism.

The theory of this experiment, however, depends on the form in which we accept the theory of undulations. In every form of the theory, the index of refraction depends on the retardation which a ray experiences on account of having to traverse a dense medium instead of a vacuum. Let us calculate this retardation.

Let there be a transparent medium whose thickness is a , and let it be supposed fixed. Let the luminiferous ether be supposed to move with velocity v in air, and with velocity v' within the medium. Let light be propagated through the ether with velocity V in air and with velocity V' within the medium. Then the absolute velocity of the light will be $v+V$ in air and $v'+V'$ within the medium, and the retardation, or difference of *time* in traversing a thickness a of the medium and an equal thickness of air, will be

$$a\left(\frac{1}{v'+V'} - \frac{1}{v+V}\right);$$

and the retardation in *distance* reckoned as at the velocity, V will be

$$a\left\{\frac{V}{V'} - 1 - \frac{v'}{V}\left(\frac{V^2}{V'^2} - \frac{v}{v'}\right) + \frac{v'^2}{V^2}\left(\frac{V^3}{V'^3} - \frac{v^2}{v'^2}\right) - \&c. \right\}.$$

Now, according to every form of the theory, $\frac{V}{V'} = \mu$, the index of refraction, and according to Fresnel's form of the theory, in which the density of the medium varies as μ^2 , the equation of continuity requires that $\frac{v}{v'} = \mu^2$. In this case the second term disappears and the retardation is $a(\mu - 1) + \text{terms in } \frac{v'^2}{V^2}$, which may be neglected, as V is more than 10,000 times v .

Hence, on Fresnel's theory, the retardation due to the prism is not sensibly affected by the motion of the earth. The same would be true on the hypothesis that the luminiferous ether near the earth's surface moves along with the earth, whatever the form of the theory of the medium.

Since the deviation of light by the prism depends entirely on the retardation

of the rays within the glass, no effect of the earth's motion on the refrangibility of light is to be expected. Professor Stokes (*Phil. Mag.*, 1846, p. 63) has also given a direct proof of this statement, and the experiment of Arago confirms it to a certain degree of exactness.

In order to test the equality of the index of refraction for light moving in opposite directions through a prism, I employed in 1864 the following arrangement.

I made use of a spectroscope constructed by Mr. Becker, and provided with a tube at right angles to the axis of the observing-telescope, carrying a transparent plate of parallel glass placed between the object-glass and its focus, so as to reflect the light which enters the tube along the axis of the telescope towards the object-glass. In this tube is placed a screen with a vertical slit, in the middle of which is a vertical spider-line so arranged that its virtual image formed by the first surface of the glass plate coincides with the crossing of the spider-lines of the telescope at the principal focus of the object-glass. This coincidence is tested by observing the cross lines through the other telescope, with the two telescopes facing each other. The eyepiece of the second telescope is then removed, and a plane mirror is placed at the focus of the object-glass, perpendicular to the axis, and the telescopes are so adjusted that light entering by the side tube is reflected down the axis of the first telescope, traverses the prisms in succession, enters the second telescope, is reflected by the mirror at its focus, and emerges from the telescope parallel to its direction at incidence; it then traverses the prisms in the reverse order, and is brought to a focus at the cross lines of the first telescope.

If the deviation of the rays in passing through the prisms from east to west differs from that produced during their passage from west to east, the image of the vertical spider-line formed by the rays which have traversed the prisms twice will not coincide with the intersection of the spider-lines as before.

I have found, however, that when the instrument is properly adjusted, the coincidence is so perfect with respect to rays of all refrangibilities, that the image of the vertical spider-line is seen with perfect distinctness, though the rays which form it have passed twice through three prisms of 60° .

If we observe the coincidence of this image with the intersection of the spider-lines at the focus when the rays pass through the prisms first in the direction of the earth's motion and return in the opposite direction, we may then reverse the whole instrument, so that the rays pursue an opposite path with respect to the earth's motion. I have tried this experiment at various times of the year since the year 1864, and have never detected the slightest effect due to the earth's motion. If the image of the spider-line is hid by the intersection of the cross lines in one position, it remains hid in precisely the same way in the other position, though a deviation corresponding to one-

twentieth of the distance of the components of the line D could be easily detected.

On the other hand, M. Fizeau * has observed a difference in the rotation of the plane of polarisation according as the ray travels in the direction of the earth's motion or in the contrary direction, and M. Ångström has observed a similar difference in phenomena of diffraction. I am not aware that either of these very difficult observations has been confirmed by repetition.

In another experiment of M. Fizeau, which seems entitled to greater confidence, he has observed that the propagation of light in a stream of water takes place with greater velocity in the direction in which the water moves than in the opposite direction, but that the acceleration is less than that which would be due to the actual velocity of the water, and that the phenomenon does not occur when air is substituted for water. This experiment seems rather to verify Fresnel's theory of the ether; but the whole question of the state of luminiferous medium near the earth, and of its connection with gross matter, is very far as yet from being settled by experiment.

JAMES CLERK MAXWELL.

June 10, 1867.

DESCRIPTION OF APPARATUS

All the experiments were made with my refractor by Alvan Clark, of 8 inches aperture and 10 feet focal length, which is mounted equatorially, and carried very smoothly by a clock-motion. As even on nights of unusual steadiness the lines in the spectra of the stars are necessarily, for several reasons, more difficult of minute discrimination of position than are those of the solar spectrum, it is important that the apparatus employed should give an ample amount of dispersion relatively to the degree of minuteness of observation which it is proposed to attempt.

In 1866 I constructed a spectroscope for the special objects of research described in this paper, which was furnished with three prisms of 60° of very dense flint glass. The solar lines were seen with great distinctness. I found, however, that, in order to obtain a separation of the lines sufficient for my purpose, an eyepiece magnifying ten or twelve diameters was necessary. Under these circumstances the stellar lines were not seen in the continued steady manner which is necessary for the trustworthy determination of the minute differences of position which were to be observed. After devoting to these observations the most favourable nights which occurred during a period of some months, I found that if success was to be obtained, it would probably be with

* *Ann. de Chimie et de Physique*, Feb. 1860.

an apparatus in which a larger number of prisms and a smaller magnifying power were employed.

The inconvenience arising from the pencils, after passing through the prisms, crossing those from the collimator when more than three or four prisms are employed, and also, in part, the circumstance that I had in my possession two very fine direct-vision prisms on Amici's principle, which had been made for me by Hofmann of Paris, induced me to attempt to combine in one instrument several simple prisms with one or two compound prisms which give direct vision. An instrument constructed in this way, as will be seen from the following description, possesses several not unimportant advantages.*

a is an adjustable slit; *b* an achromatic collimating lens of 4·5 inches focal length; *c* represents the small telescope with which the spectrum is viewed. The train of prisms consists of two compound prisms, *d* and *e*, and three simple

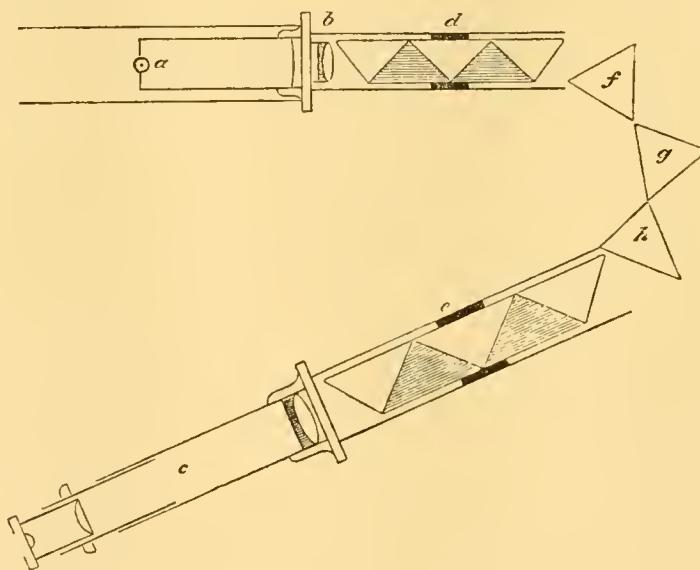


Fig. 26.

prisms, *f*, *g*, *h*. Each of the compound prisms contains five prisms, cemented together with Canada balsam. The shaded portions of the diagram represent the position of the two prisms of very dense flint glass in each compound prism. The compound prism marked *e* is much larger than the other, and is permanently connected with the telescope *c*, with which it moves. These compound prisms, which were made specially to my order by Hofmann, are of great perfection, and produced severally a dispersion fully equal to two prisms of ordinary dense flint glass. The prisms *f* and *g* were cut for me from a very fine piece of dense glass of Guinand by Messrs. Simms, and have each a refracting angle of 60°. The prism *h* was made by Mr. Browning from the

* [An apparatus in many respects superior to the one here described has been constructed since.—October 1868.]

dense flint glass manufactured by Messrs. Chance; this prism has a refracting angle of 45° . The great excellence of all these prisms is shown by the very great sharpness of definition of the bright lines of the metals when the induction-spark is taken before the slit, even when considerable magnifying power is employed on the small telescope with which the spectrum is viewed. The instrument is provided with a second collimator, of which the object-glass has a focal length of 18 inches.

The compound prism e is so fixed that it can be removed at pleasure, when the total dispersive power of the instrument is reduced from about six and a half prisms of 60° to about four and a half prisms of 60° . The facility of being able to reduce the power of the instrument has been found to be of much service for the observation of faint objects, and also on nights when the state of the atmosphere was not very favourable.

The telescope with which the spectrum is viewed is carried by a micrometer-screw, which, however, has not been employed for taking measures of the spectra, but only for the purpose of setting the telescope to the part of the spectrum which it is intended to observe. This precaution is absolutely necessary when nebulae are observed which emit light of two or three refrangibilities only.

For the purpose of the simultaneous comparisons of the light of the heavenly bodies with the lines of the terrestrial elements, the slit was provided, in the usual way, with a small prism placed over one half of it, which received the light reflected upon it from a small mirror placed opposite the electrodes. The plan of observation formerly employed, and which is described in the paper "On the Spectra of some of the Fixed Stars," was adopted to ensure perfect accuracy of relative position in the instrument between the star-spectrum and the spectrum to be compared with it, since it is possible by tilting the mirror to alter within narrow limits the position of the spectrum of the terrestrial substance relatively to that of the star. Before commencing an observation, a small alcohol lamp, in the wick of which bicarbonate of soda was placed, was fixed before the object-glass of the telescope, and then the mirror and the electrodes were so adjusted that the components of the double line D were exactly coincident in both spectra.

This plan was soon found to be very inconvenient, and even in some degree untrustworthy for the more delicate comparisons which were now attempted. An unobserved accidental displacement of the spark, or of the mirror, might cause the two spectra to differ in position by an amount equal to the whole extent of want of coincidence which it was proposed to seek for in this investigation. The observations of many nights have been rejected, from the uncertainty as to the possible existence of an accidental displacement.

Another inconvenience, so great as even to seem to diminish the hope of

ultimate success, was found to arise from the difficulty of bringing the lower margin of the star-spectrum into actual contact with the upper margin of the spectrum of the light reflected into the instrument. The lines in the spectra of the stars are not, on ordinary nights, so steady and distinct as are those of the solar spectrum. Under these difficult circumstances it is very desirable, as an assistance to the eye in its judgment of the absolute identity or otherwise of the position of lines, that the bright lines of comparison should not merely meet the dark lines in the star-spectrum, but that they should overlap them to a small extent. When the two spectra are so arranged as to be in contact, the eye is found to be influenced to some extent by the apparent straightness or otherwise of the compound line formed by the coincident, or nearly coincident lines in the two spectra.

The difficulties of observation which have been referred to were in the first instance sought to be overcome by placing the spark before the object-glass of the telescope. In some respects this method appears to be unexceptionable, but there are disadvantages connected with it. The bright lines, under these circumstances, extend across the star-spectrum, and make the simultaneous observation of dark lines, which are coincident, or nearly so with them, very difficult. When the spark is taken between open electrodes, the consequent disturbance of the air in front of the object-glass is unfavourable to good definition. An important disadvantage arises from the great diminution in the brightness of the spark from the distance (10 feet) at which it is placed from the slit; since in consequence of its nearness to the object-glass, the divergence of the light from it is diminished in a small degree only by that lens. It is obvious that, by means of a lens of short focal length placed between the spark and the object-glass, the light from the spark might be rendered parallel or even convergent; but the adjustments of such a lens, so that the pencils transmitted by it should coincide accurately in direction with the optical axis of the telescope, would be very troublesome. When two Leyden jars, connected as one jar, were interposed, and the spark was taken in air between platinum points, there was visible in the spectroscope only the brightest of the lines of the air-spectrum—namely, the double line belonging to nitrogen, which corresponds nearly to the principal line in the spectra of the gaseous nebulae. When a vacuum-tube containing hydrogen at a low tension was placed before the object-glass, the line corresponding to F was seen with sufficient distinctness, but the line in the red was visible with difficulty. Some observations, however, have been made with the spark arranged before the object-glass.

The following arrangement for admitting the light from the spark appeared to me to be free from the objections which have been referred to, and to be in all respects adapted to meet the requirements of the case. In place of the small prism, two pieces of silvered glass were securely fixed before the slit at an

angle of 45° . In a direction at right angles to that of the slit, an opening of about $\frac{1}{10}$ inch was left between the pieces of glass for the passage of the pencils from the object-glass. By means of this arrangement the spectrum of a star is seen accompanied by two spectra of comparison, one appearing above and the other below it. As the reflecting surfaces are about 0.5 inch from the slit, and the rays from the spark are divergent, the light reflected from the pieces of glass will have encroached upon the pencils from the object-glass by the time they reach the slit, and the upper and lower spectra of comparison will appear to overlap to a small extent the spectrum formed by the light from the object-glass. This condition of things is of great assistance to the eye in forming a judgment as to the absolute coincidence or otherwise of lines. For the purpose of avoiding some inconveniences which would arise from glass of the ordinary thickness, pieces of the thin glass used for the covers of microscopic objects were carefully selected, and these were silvered by floating them upon the surface of a silvering solution. In order to insure that the induction-spark should always preserve the same position relatively to the mirror, a piece of sheet gutta-percha was fixed above the silvered glass; in the plate of gutta-percha, at the proper place, a small hole was made of about $\frac{1}{20}$ inch in diameter. The ebonite clamp containing the electrodes is so fixed as to permit the point of separation of these to be adjusted exactly over the small hole in the gutta-percha. The adjustment of the parts of the apparatus was made by closing the end of the adapting-tube, by which the apparatus is attached to the telescope, with a diaphragm with a small central hole, before which a spirit-lamp was placed. When the lines from the induction-spark, in the two spectra of comparison, were seen to overlap exactly, for a short distance, the lines of sodium from the light of the lamp, the adjustment was considered perfect. The accuracy of adjustment has been confirmed by the exact coincidence of the three lines of magnesium with the component lines of δ in the spectrum of the moon.

In some cases the spectra produced by the spark are inconveniently bright for comparison with those of the stars and nebulæ. If the spark is reduced in power below a certain point, many of the lines are not then well developed; the plan, therefore, was adopted of diminishing the brightness of the spectrum, by a wedge of neutral-tint glass which can be moved at pleasure between the plate of gutta-percha and the silvered mirror.

Two eyepieces were employed with the apparatus, the one magnifying four, and the other six diameters.

The induction-coil was the same which I employed in my former observations. It was excited by a form of bichromate-of-potash battery, which I have found so exceedingly convenient for the occasional work of celestial observations that I will describe it here.

The battery, which was made for me by Mr. Ladd, consists of two large cells of ebonite, each of which contains two plates of graphite, 6 inches by $7\frac{1}{2}$ inches, connected together with copper bands. These plates are fixed into varnished plates of wood, which form covers to the cells. In each wooden cover is a slit of the length of the width of the carbon plates, by which an amalgamated zinc plate can be inserted between the plates of graphite. An important part of the arrangement is a third large cell of ebonite, which is filled with water acidulated with a few drops of sulphuric acid, and contains at the bottom some mercury. As soon as a plate is removed from the battery after use, it is rubbed clean under running water, and then immersed in the spare cell until it is again required. By this arrangement the plates are always clean and perfectly amalgamated. The solution employed to charge the battery is a saturated solution of bichromate of potash, to which about $\frac{1}{10}$ part of sulphuric acid has been added. The battery is sufficiently powerful and always ready for instant use. For the convenience of varying the power of the battery, three sets of zinc plates are kept in the spare cell; the plates are 2 inches, 4 inches, and 6 inches in width.

OBSERVATIONS OF STARS

The chief difficulties which I have had to encounter have arisen from the unsteadiness of our atmosphere. There is sufficient light from stars of the first and second magnitude for the large spectroscope described in this paper; and so far as the adjustments of the instrument are concerned, the lines in the spectra of the stars would be well defined. Unless, however, the air is very steady, the lines are seen too fitfully to permit of any certainty in the determination of coincidences of the degree of delicacy which is attempted in the present investigation. I have passed hours in the attempt to determine the position of a single line, and have then not considered that the numerous observations which I had obtained were possessed, even collectively, of sufficient weight to establish with any certainty the coincidence of the line with the one compared with it.

I prefer, therefore, to reject a large number of observations which appear unsatisfactory from this cause, and to give in this place a very few of the most trustworthy of the observations which I have made.

Sirius.—The brilliant light of this star, and the great intensity of the four strong lines of its spectrum, make it especially suitable for such an examination. The low altitude of this star in our latitude limits the period in which it can be successfully observed to about one hour on each side of the meridian.

I have confined myself to comparisons of the strong line in the position of F, with the corresponding line of the spectrum of hydrogen. My first

trials were made with hydrogen at the ordinary atmospheric pressure; the width of the band of hydrogen, under these circumstances, was greater than the line of Sirius. This line in Sirius, from some cause, is narrower relatively to the length of the spectrum, when considerable dispersion and a narrow slit are employed, than when the image of the star, rendered linear by a cylindrical lens, is observed with a single prism.*

When the large spectroscope was employed I estimated the breadth of the line to be about equal to that of the double line D. In Kirchhoff's map the line F of the solar spectrum is represented as a little more than one-fourth of the interval separating the lines D. When the spectroscope attached to the telescope was directed to the moon, the line F appeared even narrower than it is represented in Kirchhoff's map; I estimated it at about one-sixth of the apparent breadth of the corresponding line in the spectrum of Sirius. The character of the line agrees precisely with Kirchhoff's representation of the solar line F. It appears, as in the diagram, to be equally nebulous at both edges, and agrees in this respect precisely with the line of hydrogen under certain conditions of tension and temperature.

As it was obviously impossible to determine with the required accuracy the coincidence of the line of Sirius when the much broader band of hydrogen at the ordinary pressure was compared with it, I employed a vacuum-tube fixed before the object-glass. In all these observations the slit used was as narrow as possible. The air at the time of the present observations was more favourable than usual, and the line in Sirius was seen with great distinctness. The line from the spark appeared, in comparison, very narrow, not more than about one-fifth of the width of the line of Sirius. When the battery circuit was completed, the line of hydrogen could be seen distinctly upon the dark line of Sirius, and extending to some distance on both sides of the spectrum of Sirius. The observation of the comparison of the lines was made many times, and I am certain that the narrow line of hydrogen, though it appeared projected upon the dark line in Sirius, did not coincide with the middle of the line, but crossed it at a distance from the middle, which may be represented by saying that the want of coincidence was *apparently* equal to about one-third or one-fourth of the interval separating the components of the double line D. I was unable to measure directly the distance between the centre of the line of hydrogen and that of the line in the spectrum of Sirius, but several very careful estimations by means of the micrometer give a value for that distance of 0·040 of the micrometer-head. This value is probably not in error by so much as its eighth part.

Comparisons on many other nights were also made, sometimes with the vacuum-tube before the object-glass, and sometimes with the vacuum-tube

* See *Phil. Trans.* 1864, p. 42.

placed over the small hole in the gutta-percha plate. On all these occasions the numerous comparisons which were made gave for the line in Sirius a very slightly lower refrangibility than that of the line of hydrogen, but on no one occasion was the air steady enough for a satisfactory determination of the amount of difference of refrangibility.

I have not been able to detect any probable source of error in this result, and it may therefore, I believe, be received as representing a relative motion of recession between Sirius and the earth.

The probability that the substance in Sirius by which this line is produced is really hydrogen is strengthened almost to certainty by the consideration that there is a strong line in the red part of the spectrum which is also coincident with a strong line of hydrogen. There is a third line more refrangible than F, which appears to coincide with the line of hydrogen in that part of the spectrum.

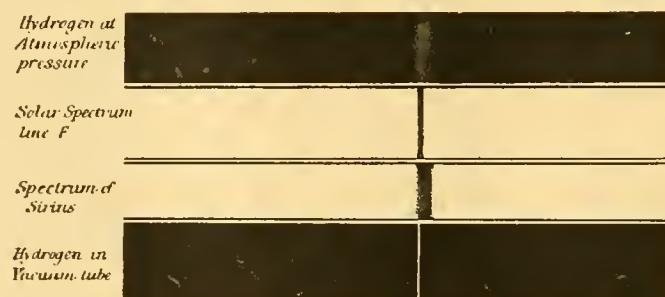


Fig 27.

As the line in Sirius is more expanded than that of the vacuum-tube, it seemed of importance to have proof from experiment that this line of hydrogen, when it becomes broad, expands equally in both directions. I made the comparison of the narrow line of the vacuum-tube with the more expanded band which appears when denser hydrogen is employed. For this purpose the intersection of the wires of the eyepiece was brought, as nearly as could be estimated, upon the middle of the expanded line which is produced by dense hydrogen. The vacuum-tube was then arranged before the slit, when the narrow line which it gives was observed to fall exactly upon the point of intersection of the wire. Under these terrestrial conditions the expansion of the line may be considered to take place to an equal amount in both directions. There is a very great probability that a similar equal expansion takes place under the conditions which determine the absorption of light by this gas in the atmosphere of Sirius, for the reason that the nebulosity at the edges of the line in the spectrum of that star is sensibly equal on both sides.

I made some attempts to compare the strong line at C with the corresponding line of hydrogen; but when the large spectroscope was employed, though the lines could be seen with tolerable distinctness, they were not bright enough to admit of a trustworthy determination of their relative position. When one of the compound prisms was removed, the lines were much more easily seen, but under these circumstances the amount of dispersion was insufficient for my present purpose.

The lines of Sirius which, in conjunction with Dr. Miller, I had compared with those of iron, magnesium, and sodium are not sufficiently well seen in our latitude for comparison, when a powerful train of prisms is employed, such as is necessary for this special inquiry.

From these observations it may, I think, be concluded that the substance in Sirius which produces the strong lines is really hydrogen, as was stated by Dr. Miller and myself in our former paper. Further, that the aggregate result of the motions of the star and the earth in space, at the time when the observations were made, was to degrade the refrangibility of the line in Sirius by an amount corresponding to 0·040 of the micrometer-screw. Now the value of the wave-lengths of 0·01 division of the micrometer at the position of F is 0·02725 millionth of a millimetre.* The total degradation of refrangibility observed amounts to 0·109 millionth of a millimetre. If the velocity of light be taken at 185,000† miles per second, and the wave-length of F at 486·50 millionths of a millimetre (Ångström's value is 486·52, Ditscheiner's 486·49), the observed alteration in period of the line in Sirius will indicate a motion of recession existing between the earth and the star of 41·4 miles per second.

Of this motion a part is due to the earth's motion in space. As the earth moves round the sun in the plane of the ecliptic, it is changing the direction of its motion at every instant. There are two positions, separated by 180°, where the effect of the earth's motion is a maximum—namely, when it is moving in the direction of the visual ray, either towards or from the star. At two other positions in its orbit, at 90° from the former positions, the earth's

* The value in wave-lengths of the divisions of the micrometer for different parts of the spectrum was determined by the aid of the tables of the wave-lengths corresponding to every tenth line of Kirchhoff's map by Dr. Wolcott Gibbs (*Silliman's Journal*, vol. xlivi., January 1867). A paper on the same subject by the Astronomer Royal, presented to the Royal Society, is not yet in print. [The Astronomer Royal's paper is contained in the *Phil. Trans.* for 1868, Part I., p. 29. The wave-lengths computed by him differ slightly from those assigned to Kirchhoff's numbers by Dr. Gibbs at the part of the spectrum under consideration in the text. The difference is due in part to the employment, by the Astronomer Royal, of Ditscheiner's later measures. These give for F the higher value of 486·87.—October 1868.]

† The new determination of the value of the solar parallax by observations of Mars requires that the usually received velocity of light, 192,000 per second, should be reduced by about the one-twenty-seventh part. The velocity, when diminished in this ratio, agrees nearly with the result obtained by Foucault from direct experiment.

motion is at right angles to the direction of the light from the star, and therefore has no influence on its refrangibility.

The effect of the earth's motion will be greatest upon the light of a star situated in the plane of the ecliptic, and will decrease as the star's latitude increases, until with respect to a star situated at the pole of the ecliptic, the earth's motion during the whole of its annual course will be perpendicular to the direction of the light coming to us from it, and will be therefore without influence on its period.

That part of the earth's resolved motion which is in the direction of the visual ray, and which has alone to be considered in this investigation, may be obtained from the following formula :

$$\text{Earth's motion towards star} = v \cos \lambda \sin (\ell - \ell'),$$

where v is earth's velocity, ℓ the earth's longitude, ℓ' the star's longitude, and λ the star's latitude.

At the time when the estimate of the amount of alteration of period of the line in Sirius was made, the earth was moving from the star with a velocity of about 12 miles per second.

There remains unaccounted for a motion of recession from the earth amounting to 29·4 miles per second, which we appear to be entitled to attribute to Sirius.

It may be not unnecessary to state that the solar motion in space, if accepted as a fact, will not materially affect this result, since, according to M. Otto Struve's calculations, the advance of the sun in space takes place with a velocity but little greater than one-fourth of the earth's motion in its orbit. If the apex of the solar motion be situated in Hercules, nearly the whole of it will be from Sirius, and will therefore diminish the velocity to be ascribed to that star.

It is interesting, in connection with the motion of Sirius deduced from these prismatic observations, to refer to the remarkable inequalities which occur in the rather large proper motion of that star. In 1851 M. Peters* showed that the variable part of the proper motion of Sirius in right ascension might be represented by supposing that Sirius revolves in an elliptic orbit, round some centre of gravity without itself, in a period of 50·093 years. This hypothesis has acquired new interest, and seems indeed to have received confirmation from direct observation by Alvan Clark's discovery of a small companion to Sirius.

Professor Safford † and Dr. Auwers ‡ have investigated the periodical

* *Astron. Nachrichten*, No. 748.

† *Proc. of the Amer. Acad.*, vol. vi.; also *Astron. Notices, Ann. Arbor*, No. 28; *Monthly Notices*, vol. xxii., p. 145.

‡ *Astron. Nachrichten*, No. 1506; *Monthly Notices*, vol. xxii., p. 148, and vol. xxv., p. 39.

variations of the proper motion of Sirius in declination, and they have found that these variations, equally with those in right ascension, would be reconcilable with an elliptic orbital motion round a centre not in Sirius. The close coincidence of the observed positions of the new satellite with those required by theory seems to show that it may be the hypothetical body suggested by Peters, though we must then suppose it to have a much greater mass, relatively to Sirius, than that which its light would indicate.

At the present time the proper motion of Sirius in declination is less than its average amount by nearly the whole of that part of it which is variable. May not this smaller apparent motion be interpreted as showing that a part of the motion of the star is *now in the direction of the visual ray?* This circumstance is of much interest in connection with the result arrived at in this paper.

Independently of the considerations connected with the variable part of the star's proper motion, it must not be forgotten that the whole of the motion which can be directly observed by us is only that portion of its real motion which is at right angles to the visual ray. Now it is precisely the other portion of it, which we could scarcely hope to learn from ordinary observations, which is revealed to us by prismatic investigations. By combining the results of both methods of research we may perhaps expect to obtain some knowledge of the real motions of the brighter stars and nebulae.

It seems therefore desirable to compare with the result obtained by the prism, the motion of Sirius which corresponds to its assumed constant proper motion. The values adopted by Mr. Main,* and inserted by the Astronomer Royal in the Greenwich "Seven-year Catalogue," are $-0''\cdot 035$ in R.A., and $+1''\cdot 24$ in N.P.D.

The parallax of Sirius from the observations of Henderson, corrected by Bessel, = $0''\cdot 150$. A recent investigation by Mr. C. Abbe † gives for the parallax the larger value of $0''\cdot 27$. If the radius of the earth's orbit be taken at its new value of 91,600,000 miles, the assumed annual constant proper motion in N.P.D. of $1''\cdot 24$ would indicate, with the parallax of Henderson, a velocity of Sirius of twenty-four miles nearly per second, with the larger parallax of Mr. Abbe, a velocity of 43·2 miles per second. It may be that in the case of Sirius we have two distinct motions, one peculiar to the star, and a second motion which it may share in common with a system of which it may form a part.

Observations and comparisons, similar to those on Sirius, have been made on α Canis Minoris, Castor, Betelgeux, Aldebaran, and some other stars. I reserve for the present the results which I have obtained, as I desire to submit these objects to a re-examination. It is seldom that the air is sufficiently favourable for the successful prosecution of this very delicate research.

* *Mem. Roy. Astron. Soc.*, vol. xix.

† *Monthly Notices R.A.S.*, vol. xxviii., p. 2.

ON THE MOTIONS OF SOME STARS TOWARDS OR FROM THE EARTH

(From *Proc. Roy. Soc.*, vol. xx., p. 379, 1872)

IN the early part of 1868 I had the honour of presenting to the Royal Society some observations on a small change of refrangibility which I had observed in a line in the spectrum of Sirius as compared with a line of hydrogen, from which it appeared that the star was moving from the earth with a velocity of about twenty-five miles per second, if the probable advance of the sun in space be taken into account.*

It is only within the last few months that I have found myself in possession of the necessary instrumental means to resume this inquiry, and since this time the prevalence of bad weather has left but few nights sufficiently fine for these delicate observations.

Some time was occupied in obtaining a perfectly trustworthy method of comparison of the spectra of stars with those of terrestrial substances, and it was not until I had arranged the spark within the tube, as described at the beginning of this note,† that I felt confidence in the results of my observations.

It may be well to state some circumstances connected with these comparisons which necessarily make the numerical estimations given farther on less accurate than I could wish. Even when spectroscope C, containing four compound prisms, and a magnifying power of 16 diameters are used, the amount of the change of refrangibility to be observed appears very small. The probable error of these estimations is therefore large, as a shift corresponding to five miles per second (about $\frac{1}{40}$ of the distance of D¹ to D²), or even a somewhat greater velocity, could not be certainly observed. The difficulty arising from the apparent smallness of the change of refrangibility is greatly increased by some other circumstances. The star's light is faint when a narrow slit is used, and the lines, except on very fine nights, cannot be steadily seen, in consequence of the movements in our atmosphere. Further, when the slit is narrow, the clock's motion is not uniform enough to keep the spectrum steadily in view; for these reasons I found it necessary to adopt the method of estimation by

* *Phil. Trans.*, 1868, pp. 529-550. As a curious instance in which later methods of observation have been partially anticipated, a reference may be made to an ingenious paper in the *Phil. Trans.* for 1783, vol. lxxiv., by the Rev. John Michell, entitled "On the means of discovering the Distance, Magnitude, &c. of the Fixed Stars, in consequence of the Diminution of the Velocity of their Light." The author suggests that by the use of a prism "we might be able to discover diminutions in the velocity of light as perhaps a hundredth, a two-hundredth, a five-hundredth, or even a thousandth part of the whole." But he then goes on to reason on the production of this diminished velocity by the attraction produced on the material particles of light by the matter of the stars, and that the diminutions stated above would be "occasioned by spheres whose diameter should be to the sun, provided they were of the same density, in the several proportions of 70, 50, 30, and 22 to 1 respectively."

† See "On the Spectrum of the Great Nebula in Orion," p. 144.

comparing the shift with a wire of known thickness, or with the interval between a pair of close lines. I found that, under the circumstances, the use of a micrometer would have given the appearance only of greater accuracy. I wish it, therefore, to be understood that I regard the following estimations as provisional only, as I hope, by means of apparatus now being constructed, to be able to get more accurate determinations of the velocity of the motions.

Sirius.—The comparison of the line at F with the corresponding line of hydrogen was made on several nights from January 18 to March 5. Spectroscope C and eyepieces 2 and 3 were used. These observations confirm the conclusion arrived at in my former paper, that the star is moving from the earth; but they ascribe to the star a velocity smaller than that which I then obtained.

These observations on different days show a change of refrangibility corresponding to a velocity of from 26 to 36 miles per second. The part of the earth's orbital motion from the star varied on these days from 10 to 14 miles per second. We may take, therefore, 18 to 22 miles per second as due to the star.

The difference of this estimate, which is probably below rather than in excess of the true amount, from that which I formerly made may be due in part or entirely to the less perfect instruments then at my command. At the same time, if Sirius be moving in an elliptic orbit, as suggested by Dr. Peters, that part of the star's proper motion which is in the direction of the visual ray would constantly vary.*

Betelgeux (α Orionis).—In the early observations of Dr. Miller and myself on this star, we found that there are no strong lines coincident with the hydrogen lines at C and F. The line H α falls on the less refrangible side of a small group of strong lines, and H β occurs in the space between two groups of strong lines where the lines are faint. On one night of unusual steadiness of the air, when the finer lines in the star's spectrum were seen with more than ordinary distinctness, I was able with the more powerful instruments now at my command to see a narrow defined line in the red apparently coincident with H α , and a similar line at the position of H β . These lines are much less intense than the lines C and F in the solar spectrum; there are certainly no bright lines in the star's spectrum at these places.

* Dr. H. Vogel at Bothkamp seems to have repeated my observations on Sirius with the necessary care. He says (*Astronom. Nachrichten*, No. 1864): "Mit der eben beschriebenen Anordnung gelang es Herrn Dr. Lohse und mir am 22. März (1871) bei ganz vorzüglicher Luft die Nichtcoincidenz der drei Wasserstofflinien H α , H β , und H γ , der Geissler'schen Röhre mit den entsprechenden Linien des Sirius-spectrum zu sehen . . . mit Berücksichtigung der Geschwindigkeit der Erde zur Zeit der Beobachtung berechnet sich die Geschwindigkeit mit welcher sich Sirius von der Erde bewegt zu 100 Meilen in der Secunde, wogegen Procyon sich 13.8 Meilen in der Secunde von unserer Erde entfernen würde."

The most suitable lines in this star for comparison with terrestrial substances for ascertaining the star's motion are the lines of sodium and of magnesium. The double character of the one line agreeing exactly with that of sodium, and the further circumstance that the more refrangible of the lines is the stronger one, as is the case in the spectrum of sodium and in the solar spectrum, and the relative distances from each other and comparative brightness of the three lines, which correspond precisely to the triple group of magnesium, can allow of no doubt that these lines in the star are really produced by the vapours of these substances existing there, and that we may therefore safely take any small displacement of either set of lines to show a motion of the star towards or from the earth. The lines due to sodium are perhaps more intense, but are as narrow and defined as the lines D_1 , D_2 , in the solar spectrum : they fall, however, within a group of very fine lines ; this circumstance may possibly account for the nebulous character which has been assigned to them by some observers.

The bright lines of sodium were compared with spectroscope B and eyepiece 3 ; they appeared to fall very slightly above the pair in the star, showing that the stellar lines had been degraded by the star's motion from the earth. The amount of displacement was estimated at about one-fifth of the distance of D_1 from D_2 , which is probably rather smaller than the true amount. This estimation would give a velocity of separation of 37 miles per second. At the time of observation the earth was moving from the star at about 15 miles per second, leaving 29 miles to be due to the star.

When magnesium was compared, a shift in the same direction, and corresponding in extent to about the same velocity of recession, was observed ; but, in consequence of other lines in the star at this place, the former estimation, based on the displacement of the lines of sodium, was considered to be more satisfactory.

Rigel.—The lines of hydrogen are strong in the spectrum of this star, and are suitable for comparison.

The line $H\beta$ is not so broad as it appears in the spectrum of Sirius, but is stronger than F in the solar spectrum : this line was compared by means of spectroscope C and eyepieces 2 and 3. The line of terrestrial hydrogen falls above the middle of the line in the star ; the star is therefore receding from the earth. The velocity of recession may be estimated as rather smaller than Sirius, probably about 30 miles per second, the earth at the time of observation moving from the star with a velocity of 15 miles, leaving about 15 miles as due to the star. This estimate is probably rather smaller than the true velocity of the star.

Castor.—The spectra of the two component stars of this double star blend in the spectroscope into one spectrum. The line $H\beta$ is rather broad, nearly as much so as the same line in the spectrum of Sirius.

The narrow line of rarefied hydrogen was compared in spectroscope B with eyepiece 3; it appeared to fall on the more refrangible side of the middle of the line in the star, leaving more of the dark line on the side towards the red. The shift seemed to be rather greater than that in Sirius, and may probably be taken at from 40 to 45 miles per second; but the earth's orbital motion was nearly 17 miles from the star, thus leaving about 25 miles for the apparent velocity of the star. This result rests at present on observations on one night only, but they seemed at the time to be satisfactory.

Regulus.—The line at F rather broad. The corresponding line of hydrogen falls on the more refrangible side of the middle of the dark line in the star. The air was unfavourable on all the evenings of comparison; a rough estimate gives a velocity of from 30 to 35 miles per second. The earth's motion was 18 miles, leaving from 12 to 17 miles for the velocity of recession between the star and the sun.

β and δ Leonis.—These stars were compared with hydrogen; they appear to be moving from the earth, but the want of steadiness in the air prevented me from making a satisfactory estimate of their velocity. I suspected their motion to be rather smaller than that of Regulus.

β, γ, δ, ε, ζ Ursæ majoris.—All these stars have similar spectra, in which the line F is strong, though there are small differences in the breadth of the line. They were compared with hydrogen, and appear to be moving from our system with about the same velocity. Probably their motion may be taken to be not far from 30 miles per second. The earth's motion at the time of observation was from 9 miles to 13 miles from these stars, leaving a probable velocity of recession of 17 to 21 miles per second. In the case of the double star ζ , the spectrum consisted of the light of both stars.

η Ursæ majoris was also compared with hydrogen. I believe it shows a motion from the earth, but the observations of this star are at present less satisfactory.

α Virginis and α Coronæ borealis.—These stars were compared with hydrogen. I suspect that they are receding, but I have not had nights sufficiently fine to enable me to make satisfactory observations of these stars.

In addition to these stars some observations (which are less satisfactory on account of the unfavourable weather at the time) appear to show that the stars Procyon, Capella, and possibly Aldebaran, are moving from the earth.

The stars which follow have a motion of approach.

Arcturus.—In the spectrum of this star the lines of hydrogen, of magnesium, and of sodium are sufficiently distinct for comparison. I found the comparison could be most satisfactorily made with magnesium.

The bright lines of magnesium fall on the less refrangible side of the corresponding dark lines in the star's spectrum, showing that the star is

approaching the earth. I estimated the shift at about $\frac{1}{5}$ to $\frac{1}{4}$ of the interval between Mg_2 and Mg_3 ; this amount of displacement would indicate a velocity of approach of 50 miles per second. To this velocity must be added the earth's orbital motion from the star of 5·25 miles per second, increasing the star's motion to 55 miles per second.

When I can get favourable weather, I hope to obtain independent estimations from the lines of sodium and of hydrogen.

a Lyrae.—In the spectrum of Vega the line corresponding to $H\beta$ is strong and broad. Comparisons were made on several nights, but on one evening only was the air favourable. The observations are accordant in showing that the narrow bright line from a Geissler's tube falls on the less refrangible side of the middle of the line in the star, thus leaving more of the line on the side towards the violet. The estimations give a motion of approach between the earth and the star of from 40 to 50 miles per second, to which must be added 3·9 miles for the earth's motion from the star.

a Cygni.—The hydrogen line at F in the spectrum of this star is narrower than in the spectrum of Sirius and of *a Lyrae*, though probably rather broader than the same line in the solar spectrum. I have at present observations made on two evenings only, on both of which the state of the air was unfavourable for the comparison of this line with that of terrestrial hydrogen. They give to the star a motion of approach of about 30 miles per second, which would have to be increased by 9 miles, the velocity at the time of the earth from the star.

Pollux.—The lines of magnesium and those of sodium are very distinct in the spectrum of this star. As the air was not very steady at the time of my observations, I found it more satisfactory to use for comparison the lines of magnesium, which are rather stronger than those of sodium. The three lines of magnesium appeared to be less refrangible than the corresponding dark lines in the spectrum of the star by about one-sixth of the interval from Mg_2 to Mg_3 . This estimation would represent a velocity of approach equal to about 32 miles per second. The earth's motion from the star was 17·5 miles, which increases the apparent velocity of approach to 49 miles per second. On one evening only was the air favourable enough for a numerical estimate, but the observations were entered in my Observatory book as satisfactory.

a Ursæ majoris.—The spectrum of this star is different from the spectra of the other bright stars of this constellation. The line at F is not so strong, while the lines at b are more distinct, and are sufficiently strong for comparison with the bright lines of magnesium. The bright lines of this metal fall on the less refrangible side of the dark lines, and show a motion of approach of from 35 to 50 miles per second. The earth's motion of 11·8 miles from the star must be added.

γ Leonis and ϵ Boötis.—In both these double stars the compound spectrum due to the light of both component stars was observed. Both stars are most conveniently compared with magnesium. I do not consider my observations of these stars as quite satisfactory, but they seem to show a movement of approach; but further observations are desirable.

The stars γ Cygni, α Pegasi, γ Pegasi, and α Andromedæ were compared with hydrogen on one night only. It is probable that these stars are approaching the earth, but I wish to re-observe them before any numerical estimate is given of their motion.

γ Cassiopeiæ.—On two nights I compared the bright lines which are present in its spectrum at C and F with the bright lines of terrestrial hydrogen. The coincidence appeared nearly perfect in spectroscope C with eyepieces 2 and 3; but on the night of best definition I suspected a minute displacement of the bright line towards the red when compared with H β . As the earth's orbital motion from the star at the time was very small, about 3.25 miles per second, which corresponds to a shift that could not be detected in the spectroscope, it seems probable that γ Cassiopeiæ has a small motion of recession.

In the calculation of the estimated velocities the wave-lengths employed are those given by Ångström in his "Recherches sur le spectre solaire" (Upsal, 1868). The velocity of light was taken at 185,000 miles per second.

The velocities of approach and of recession which have been assigned to the stars in this paper represent the whole of the motion in the line of sight which exists between them and the sun. As we know that the sun is moving in space, a certain part of these observed velocities must be due to the solar motion. I have not attempted to make this correction, because, though the direction of the sun's motion seems to be satisfactorily ascertained, any estimate that can be made at present of the actual velocity with which he is advancing must rest upon suppositions, more or less arbitrary, of the average distance of stars of different magnitudes. It seems not improbable that this part of the stars' motions may be larger than would result from Otto Struve's calculations, which give, on the supposition that the average parallax of a star of the first magnitude is equal to 0".209, a velocity but little greater than one-fourth of the earth's annual motion in its orbit.

It will be observed that, speaking generally, the stars which the spectroscope shows to be moving from the earth (Sirius, Betelgeux, Rigel, Procyon) are situated in a part of the heavens opposite to Hercules, towards which the sun is advancing, while the stars in the neighbourhood of this region, as Arcturus, Vega, α Cygni, show a motion of approach. There are in the stars already observed exceptions to this general statement; and there are some other considerations which appear to show that the sun's motion in space is not the

only or even, in all cases, as it may be found, the chief cause of the observed proper motions of the stars.*

There can be little doubt but that in the observed stellar movements we have to do with two other independent motions—namely, a movement common to certain groups of stars, and also a motion peculiar to each star.

Mr. Proctor has brought to light strong evidence in favour of the drift of stars in groups having a community of motion by his graphical investigation of the proper motions of all the stars in the catalogues of Mr. Main and Mr. Stone.† The probability of the stars being collected into systems was early suggested by Michell and the elder Herschel.‡ One of the most remarkable instances pointed out by Mr. Proctor are the stars β , γ , δ , ϵ , ζ of the Great Bear, which have a community of proper motions,§ while α and η of the same constellation have a proper motion in the opposite direction. Now, the spectroscopic observations show that the stars β , γ , δ , ϵ , ζ have also a common motion of recession, while the star α is approaching the earth. The star η , indeed, appears to be moving from us, but it is too far from α to be regarded as a companion to that star.

Although it was not to be expected that a concurrence would always be found between the proper motions which indicate the apparent motions at right angles to the line of sight and the radial motions as discovered by the spectroscope, still it is interesting to remark that in the case of the stars Castor and Pollux, one of which is approaching and the other receding, their proper motions also are different in direction and in amount; and further, that γ Leonis,

* As the velocities assigned to the stars are, for reasons already stated, provisional only, I feel some hesitation in drawing from them the obvious conclusions which they would suggest. The velocities given in the tables for those stars which are moving in direction in accordance with the sun's motion towards Hercules do not bear to each other the relation which they should have if they were mainly produced by the sun's motion. Even for these stars, therefore, we must look elsewhere for the cause to which they are chiefly due.

† See "Preliminary Paper on certain Drifting Motions of the Stars," *Proc. Roy. Soc.*, vol. xviii., p. 169.

‡ Sir William Herschel writes: "Mr. Michell's admirable idea of the stars being collected into systems appears to be extremely well founded, and is every day more confirmed by observations, though this does not take away the probability of many stars being still as it were solitary, or, if I may use the expression, intersystematical. . . . A star, or sun such as ours, may have a proper motion within its own system of stars, while at the same time the whole starry system to which it belongs may have another proper motion totally different in quantity and direction." Herschel further says, "And should there be found in any particular part of the heavens a concurrence of proper motions of quite a different direction, we shall then begin to form some conjectures which stars may possibly belong to ours, and which to other systems."—*Phil. Trans.*, 1783, pp. 276, 277.

§ Mr. Proctor, speaking of these stars, says: "Their drift is, I think, most significant. If, in truth, the parallelism and equality of motion are to be regarded as accidental, the coincidence is one of most remarkable character. But such an interpretation can hardly be looked upon as admissible, when we remember that the peculiarity is only one of a series of instances, some of which are scarcely less striking."—"Other Worlds than Ours," p. 269. See Paper in *Proc. Roy. Soc.*, vol. xviii., p. 170.

which has an opposite radial motion to α and β of the same constellation, differs from these stars in the direction of its proper motion.

It scarcely needs remark that the difference in breadth of the line H β in different stars affords us information of the difference of density of the gas by which the lines of absorption are produced. A discussion of the observations in reference to this point, and other considerations on the physical condition of the stars and nebulae, I prefer to reserve for the present.

TABLE I.—STARS MOVING FROM SUN

Star.	Compared with	Apparent motion.	Earth's motion.	Motion from sun.
Sirius	H	26 to 36	-10 to 14	18 to 22
Betelgeux	Na	37	-15	22
Rigel	H	30	-15	15
Castor	H	40 to 45	-17	23 to 28
Regulus	H	30 to 35	-18	12 to 17
β Ursæ majoris	H			
γ " "	H			
δ " "	H			
ϵ " "	H			
ζ " "	H			
β Leonis	H			
δ Leonis	H			
η Ursæ majoris	H			
α Virginis	H			
α Coronæ borealis	H			
Procyon	H			
Capella	H			
Aldebaran?	Mg			
γ Cassiopeiæ	H			

TABLE II.—STARS APPROACHING THE SUN

Star.	Compared with	Apparent motion.	Earth's motion.	Motion towards sun.
Arcturus	Mg	50	+ 5	55
Vega	H	40 to 50	+ 3.9	44 to 54
α Cygni	H	30	+ 9	39
Pollux	Mg	32	+ 17	49
α Ursæ majoris	Mg	35 to 50	+ 11	46 to 60
γ Leonis	Mg			
ϵ Boötis	Mg			
γ Cygni	H			
α Pegasi	H			
γ PEGASI?	H			
α Andromedæ	H			

[Though my original observations for the purpose of detecting motion in the line of sight were undertaken with a full understanding of the many

careful precautions which are necessary to avoid instrumental and other sources of possible error, as my papers themselves show, yet it was a task almost beyond what was possible to accomplish without some uncertain results, with my instrumental means, and by eye-observations. It was, therefore, not improbable that some of the numerical velocities might not be confirmed by later observations.

In 1880, with the introduction of the dry plate (which I was the first to use astronomically), I resumed successfully my early attempts in 1862 to photograph the spectra of stars (see p. 62), and made preliminary trials of photographing star spectra on the same plate together with terrestrial spectra for the determination of motion in the line of sight.

It was only at a later date, in 1888, after dry plates of more adequate sensitiveness had been provided by photographers, that Vogel, at Potsdam, showed that by means of photography the spectroscopic method of determining celestial motions in the line of sight could well come within the range of the ordinary routine work of an observatory. 1909.]

ON THE MOTIONS OF SOME OF THE NEBULÆ TOWARDS OR FROM THE EARTH

(From *Proc. Roy. Soc.*, vol. xxii., p. 251, 1874)

THE observations on the motions of some of the stars towards and from the earth which I had the honour to present to the Royal Society in 1872 appeared to show, from the position in the heavens of the approaching and receding stars, as well as from the relative velocities of their approach and recession, that the sun's motion in space could not be regarded as the sole cause of these motions. "There can be little doubt but that in the observed stellar movements we have to do with two other independent motions—namely, a movement common to certain groups of stars, and also a motion peculiar to each star."*

It presented itself to me as a matter of some importance to endeavour to extend this inquiry to the nebulae, as it seemed possible that some light might be thrown on the cosmical relations of the gaseous nebulae to the stars and to our stellar system by observations of their motions of recession and of approach.

Since the date of the paper to which I have referred, I have availed myself of the nights sufficiently fine (unusually few even for our unfavourable climate) to make observations on this point.

The inquiry was found to be one of great difficulty, from the faintness of

* *Proc. Roy. Soc.*, vol. xx., p. 392.

the objects and the very minute alteration in position in the spectrum which had to be observed.

At first the inquiry appeared hopeless, from the circumstance that the brightest line in the nebular spectrum is not sufficiently coincident in character and position with the brightest line in the spectrum of nitrogen to permit this line to be used as a fiducial line of comparison. The line in the spectrum of the nebulae is narrow and defined, while the line of nitrogen is double, and each component is nebulous and broader than the line of the nebulae. The nebular line is apparently coincident with the middle of the less refrangible line of the double line of nitrogen.*

The third and fourth lines of the nebular spectrum are undoubtedly those of hydrogen; but their great faintness makes it impossible to use them as lines of comparison under the necessary conditions of great dispersive power except in the case of the brightest nebulae.

The second line, as I showed in the paper to which I referred, is sensibly coincident with an iron line, wave-length 495·7; but this line is inconveniently faint, except in the brightest nebulae.

In the course of some other experiments my attention was directed to a line in the spectrum of lead which falls upon the less refrangible of the components of the double line of nitrogen. This line appeared to meet the requirements of the case, as it is narrow, of a width corresponding to the slit, defined at both edges, and in the position in the spectrum of the brightest of the lines of the nebulae.

In December 1872 I compared this line directly with the first line in the spectrum of the Great Nebula in Orion. I was delighted to find this line sufficiently coincident in position to serve as a fiducial line of comparison.

I am not prepared to say that the coincidence is perfect; on the contrary, I believe that if greater prism-power could be brought to bear upon the nebulae, the line in the lead spectrum would be found to be in a small degree more refrangible than the line in the nebulae.

The spectroscope employed in these observations contains two compound prisms, each giving a dispersion of 9° 6' from A to H. A magnifying power of 16 diameters was used.

In the simultaneous observation of the two lines it was found that if the lead line was made rather less bright than the nebular line, the small excess of apparent breadth of this latter line, from its greater brightness, appeared to overlap the lead line to a very small amount on its less refrangible side, so that the more refrangible sides of the two lines appeared to be in a straight line across the spectrum. This line could be therefore conveniently employed as a fiducial line in the observations I had in view.

* *Proc. Roy. Soc.*, vol. xx., p. 380.

In my own map of the spectrum of lead this line is not given. In Thalén's map (1868) the line is represented by a short line to show that, under the conditions of spark under which Thalén observed, this line was emitted by those portions only of the vapour of lead which are close to the electrodes.

I find that by alterations of the character of the spark this line becomes long, and reaches from electrode to electrode. As some of those conditions (such as the absence of the Leyden jars, or the close approximation of the electrodes when the Leyden jars are in circuit) are those in which the lines of nitrogen of the air in which the spark is taken are faint or absent, the circumstance of the line becoming bright and long or faint and short, inversely as the line of nitrogen, suggested to me the possibility that the line might be due not to the vapour of lead, but to some combination of nitrogen under the presence of lead vapour. As, however, this line is bright under similar conditions when the spark is taken in a current of hydrogen, this supposition cannot be correct.

A condition of the spark may be obtained in which the strongest lines of the ordinary lead spectrum are scarcely visible, and the line under consideration becomes the strongest in the spectrum, with the exception of the bright line in the extreme violet.

I need scarcely remark that the circumstance of making use of this line for the purpose of a standard line of comparison is not to be taken as affording any evidence in favour of the existence of lead in the nebulae.

Each nebula was observed on several nights, so that the whole observing time of the past year was devoted to this inquiry. In no instance was any change of relative position of the nebular line and the lead line detected.

It follows that none of the nebulae observed shows a motion of translation so great as 25 miles per second, including the earth's motion at the time. This motion must be considered in the results to be drawn from the observations; for if the earth's motion be, say, 10 miles per second from the nebula, then the nebula would not be receding with a velocity greater than 15 miles per second; but the nebula might be approaching with velocity as great as 35 miles per second, because 10 miles of this velocity would be destroyed by the earth's motion in the contrary direction.

The observations seem to show that the gaseous nebulae as a class have not proper motions so great as the bright stars. It may be remarked that two other kinds of motion may exist in the nebulae, and, if sufficiently rapid, may be detected by the spectroscope: (1) a motion of rotation in planetary nebulae, which might be discovered by placing the slit of the instrument on opposite limbs of the nebulae; (2) a motion of translation in the visual direction of some portions of the nebulous matter within the nebula, which might be found by comparing the different parts of a large and bright nebula.

Sir William Herschel states that "nebulæ were generally detected in certain directions rather than in others, that the spaces preceding them were generally quite deprived of stars, that the nebulæ appeared some time after among stars of a certain considerable size and but seldom among very small stars, that when I came to one nebula I found several more in the same neighbourhood, and afterwards a considerable time passed before I came to another parcel."*

Since the existence of real nebulæ has been established by the use of the spectroscope, Mr. Proctor† and Professor D'Arrest‡ have called attention to the relation of position which the gaseous nebulæ hold to the Milky Way and the sidereal system.

It was with the hope of adding to our information on this point that these observations of the motions of the nebulæ were undertaken.

In the following list the numbers are taken from Sir J. Herschel's "General Catalogue of Nebulæ." The earth's motion given is the mean of the motions of the different days of observation. §

No.	h.	H.	Others.	Earth's motion from Nebula.
1179	360	—	M. 42	7 miles per second.
4234	1970	—	Σ. 5	12 „ „ „
4373	—	IV. 37.	—	1 „ „ „
4390	2000	—	Σ. 6	2 „ „ „
4447	2023	—	M. 57	3 „ „ „
4510	2047	IV. 51.	—	14 „ „ „
4964	2241	IV. 18.	—	13 „ „ „

LETTER IN REPLY TO FATHER SECCHI'S LETTER ON THE DISPLACEMENT OF THE STELLAR LINES

(From *Phil. Mag.*, July, 1876)

TO THE EDITORS OF THE "PHILOSOPHICAL MAGAZINE AND JOURNAL"

GENTLEMEN,

May I ask you to insert in the next number of the *Philosophical Magazine* the following translation of a letter which I have addressed to

* *Phil. Trans.*, 1784, p. 448. † "Other Worlds than Ours," pp. 280-290.

‡ *Astronom. Nachrichten*, No. 1908, p. 190.

§ [Some sixteen years later, with the more powerful instruments of the Lick Observatory, Keeler succeeded in detecting motions in the line of sight of several nebulæ. He sums up his results:—"The distance between the great Nebula of Orion and the sun is increasing at the rate of $11^{\circ} \pm 0^{\circ}8$ miles per second. . . The nebulæ are moving in space with velocities of the order of those of the stars. . . An attempt to detect rotation of a planetary nebula gave a negative result." *Publications of the Lick Observatory*, vol. iii., p. 16c, 1894.]

MM. les Secrétaires perpétuels of the Académie des Sciences in reply to the letter from Father Secchi, of which a translation appeared in the Supplementary Number of your Magazine for June?

Yours, etc.,

WILLIAM HUGGINS.

June 7, 1876.

I hesitate to occupy the time of the Academy with a few words in reply to a letter from Father Secchi, read on April 3, especially because Mr. Christie, of Greenwich, has communicated to the Royal Astronomical Society a summary of the results recently observed at Greenwich, which agree in a remarkable way with my observations on the same stars. It is true that there were discordances among the early Greenwich observations; but these were due for the most part to the apparatus, which was not in all respects sufficiently trustworthy. Mr. Christie compares his results with mine in the following table. The figures indicate the velocity of approach or of recession in English miles.

A Comparison of Star Motions in Line of Sight.

+ = recession. — = approach.

Star.	Huggins.	Greenwich.
α Andromedæ	—	-35
Aldebaran	+?	+
Capella	+	+20
Rigel	+	+
Betelgeux	+22	+75
Sirius	+18-29	+25
Castor	+23-28	+25
Procyon	+	+40
Pollux	-49	—
Regulus	+12-17	+30
β Ursæ Majoris	+17-21	+
α Ursæ Majoris	-46-60	—
β Leonis	+?	—
Spica	+	+
η Ursæ Majoris	+?	—
Arcturus	-55	-35
ϵ Boötis	-?	—
α Coronæ	+	+
Vega	-44-54	-37
α Cygni	-39	-50
α Pegasi	—	-27

Mr. Christie remarks: "Notwithstanding these difficulties, it is gratifying to find that out of the list of twenty-one stars which have been observed both by Dr. Huggins and Mr. Maunder there are only two cases of discordance,

and for both these stars Dr. Huggins has expressed himself as dissatisfied with his observations; whilst the Greenwich results for these stars rest on too few observations at present."

Since this paper was presented to the Royal Astronomical Society, the displacement of the Fraunhofer lines in the spectrum of Venus has been observed at Greenwich; and it agrees in direction with the known movement of that planet.

It is not necessary for me to investigate the causes of Father Secchi's want of success. It is sufficient to say that from the first I considered the obtaining of the assurance that the comparison of the star-spectrum with that of a terrestrial substance was not in the very least affected by the motions of the telescope to be obviously one of the very first and most necessary precautions to take.

Father Secchi writes: "Nous acquîmes la conviction que la raie pouvait paraître constamment d'un côté ou de l'autre, selon la disposition de l'instrument sans que l'observateur eût un indice assez sûr pour reconnaître l'illusion dont il était victime." Such an illusion was scarcely possible in the method which I employed, because from the first I was careful to add to other necessary precautions, that of directing frequently the telescope with the spectroscope attached to the moon, when the triple line b always coincided perfectly with the three bright lines of magnesium. When the instrument, without any possible derangement, was again directed to the star, the same displacement of the line was seen which had been observed previously.

It is also not necessary for me to state the special precautions which have to be taken when a stellar line "très-large et estampée à son bord" has to be compared with the bright line β of hydrogen, because many of the comparisons were made with narrow and defined stellar lines with the lines of magnesium and of sodium. The displacement due to the approach of Arcturus was observed not only in the case of the line F with hydrogen, but also, in the case of the triple line b , with the three lines of magnesium, and the double line D with the two lines of sodium.

The observations of the displacements of lines in the spectra of stars are necessarily, from their nature, of extreme delicacy; and success can be expected only when suitable care and precautions are taken.

Father Secchi says (p. 762), "M. Huggins reprit peu après la question." The application of the spectroscope to the movements of the heavenly bodies was entirely original on my part. It is true that Father Secchi's letter describing his negative results appeared in the *Comptes rendus* for March 2, 1868, while my paper was presented to the Royal Society the following month, April 23, 1868; but my observations for the most part, as is stated in my paper, were made during the preceding year. The idea of the method was familiar to Dr. Miller and myself at the time of our comparisons of stellar with terrestrial spectra in 1862-3 (see *Phil. Trans.*, 1868, p. 529).

HISTORICAL NOTE ON THE SPECTROSCOPIC METHOD OF
DETERMINING MOTION IN THE LINE OF SIGHT

(From a letter in *The Observatory* for December, 1901; also *Astrophys. Journ.*, vol. xiv., p. 369)

GENTLEMEN,—

It is always with extreme reluctance that I write on any personal matter. In Sir David Gill's recent Address at the Cape, printed in your last number, the statement appears that about 1865 my "attention was directed by Clerk Maxwell to the possibility of the new astronomy" (determination of motion in the line of sight).

So far from this having been the case, the method suggested itself to me directly from Doppler's work, some time in 1862—1863. Among the first words of my paper on the subject in *Phil. Trans.*, 1868, are the following: "We were fully aware at the time (1863) . . . that these comparisons might serve to tell something of the motions of the stars relatively to our system" (p. 529).

The inclusion of Clerk Maxwell's letter in my paper came about in this way. Wishing to make the historical introduction to my paper as complete as possible, I asked my friend, Clerk Maxwell, in 1867, to give me an account of some experiments which I had heard he had been making to detect the influence of motion on the refrangibility of light. His letter, which I did not receive until June 1867, appeared to me to be of so much interest, that instead of making extracts from it I requested his permission to print it in full in my paper. Clerk Maxwell's reply, which I quote from a letter dated March 23, 1868, shows clearly that my work had been independent, and not undertaken in consequence of a suggestion of his. His words are: "If it appears to you that what I sent you last summer would answer as part of your paper, it would be very agreeable to me to have it placed beside your own work, so that if it should contain anything not applicable to your methods, or to which your methods are not applicable, the difference may be seen to be the effect of independent working, and not of opposition or criticism."

Yours faithfully,

WILLIAM HUGGINS.

UPPER TULSE HILL,
November 9, 1901.

HISTORICAL NOTE

It may be of historical interest to put on record that about 1870, I made several attempts to obtain a shift, due to motion in the line of sight, of the

bright lines of a vacuum tube through which a discharge was taking place, when viewed end-on, but without success. At that time the separation of the canalstrahlen had not been effected, in which discharge recently the displacement of the lines of hydrogen by motion in the line of sight has been photographed by Stark, and also subsequently, at the Cavendish Laboratory.
[1909.]

Section V
NEW OR TEMPORARY STARS



LIST OF PAPERS

- "On the Spectrum of a New Star in Corona Borealis. (And Dr. Miller.)
Proc. Roy. Soc., vol. xv., p. 146. *Phil. Mag.*, vol. xxxii., p. 1.
1866. P. 238.
- "On the Temporary Outburst of Light in a Star in Corona Borealis."
(Article)
Quart. Journ. Sci., 1866, vol. iii., p. 376.
- "On the Spectrum of the Stella Nova visible on the Great Nebula in
Andromeda.
Report Brit. Assoc., 1885, p. 935. P. 242.
- "Preliminary Note on Nova Aurigæ." (And Mrs. Huggins.)
Proc. Roy. Soc., vol. l., p. 465. 1892. P. 243.
- "On Nova Aurigæ." (And Mrs. Huggins.)
Proc. Roy. Soc., vol. li., p. 487. 1892. P. 244.
- "On the Bright Bands in the Present Spectrum of Nova Aurigæ." (And
Mrs. Huggins.)
Proc. Roy. Soc., vol. liv., p. 30. 1893. P. 254.

HISTORICAL STATEMENT

(From *The Nineteenth Century Review*, June 1897)

I PASS at once to a primary spectroscopic observation of one of those rare and strange sights of the heavens, of which only about nineteen have been recorded in as many centuries :

. . . those far stars that come in sight
Once in a century.

On May 18, 1866, at 5 p.m., a letter came with the address "Tuam," from an unknown correspondent, one John Birmingham. Mr. Birmingham afterwards became well known by his observations on variable stars, and especially by his valuable catalogue of Red Stars in 1877. The letter ran :

"I beg to direct your attention to a new star which I observed last Saturday night, and which must be a most interesting object for spectrum analysis. It is situated in Cor. Bor.; and is very brilliant, of about the second magnitude. I sent an account of it to *The Times* yesterday; but as that journal is not likely to publish communications from this part of the world, I scarcely think that it will find a place for mine."

Fortunately the evening was fine, and as soon as it was dusk I looked, with not a little scepticism, I freely confess, at the place of the sky named in the letter. To my great joy, there shone a bright new star, giving a new aspect to the Northern Crown; of the order doubtless of the splendid temporary star of 1572, which Tycho supposed to be generated from the ethereal substance of the Milky Way, and afterwards dissipated by the sun, or dissolved from some internal cause.

I sent a messenger for my friend Dr. Miller; and an hour later we directed the telescope, with spectroscope attached, to the blazing star. Later in the evening a letter arrived from Mr. Baxendale, who had independently discovered the star on the 15th.

By this evening, the 18th, the star had already fallen in brightness below the third magnitude. The view in the spectroscope was strange, and up to

that time unprecedented. Upon a spectrum of the solar order, with its numberless dark lines, shone out brilliantly a few very bright lines. There was little doubt that at least two of these lines belonged to hydrogen. The great brilliancy of these lines as compared with the parts of the continuous spectrum upon which they fell suggested a temperature for the gas emitting them higher than that of the star's photosphere.

Few of days, as indeed had been its forebears appearing at long intervals, the new star waned with a rapidity little less remarkable than was the suddenness of its outburst, without visible descent, all armed in a full panoply of light from the moment of its birth. A few hours only before Birmingham saw it blazing with second-magnitude splendour, Schmidt, observing at Athens, could testify that no outburst had taken place. Rapid was the decline of its light, falling in twelve days from the second down to the eighth magnitude.

 It was obvious to us that no very considerable mass of matter could cool down from the high temperature indicated by the bright lines in so short a time. At the same time, it was not less clear that the extent of the mass of the fervid gas must be on a very grand scale indeed, for a star at its undoubted distance from us to take on so great a splendour. These considerations led us to suggest some sudden and vast convulsion, which had taken place in a star so far cooled down as to give but little light, or even to be partially crusted over, by volcanic forces, or by the disturbing approach or partial collision of another dark star. The essential character of the explanation lay in the suggestion of a possible chemical combination of some of the escaping highly heated gases from within, when cooled by the sudden expansion, which might give rise to an outburst of flame at once very brilliant and of very short duration.

The more precise statement of what occurred during our observations, as made afterwards from the pulpit of one of our cathedrals—"That from afar astronomers had seen a world on fire go out in smoke and ashes"—must be put down to an excess of the theological imagination.

ON THE SPECTRUM OF A NEW STAR IN CORONA BOREALIS*

(From *Proc. Roy. Soc.*, vol. xv., p. 146; and *Phil. Mag.*, 1866, vol. xxxii., p. 1)

YESTERDAY, May 16, one of us received a note from Mr. John Birmingham, of Tuam, stating that he had observed on the night of May 12 a new star in

* The Astronomer Royal wrote to one of us on the 18th, "Last night we got a meridian observation of it; on a rough reduction its elements are—

R.A. 1866, May 17	$15^{\text{h}} 53^{\text{m}} 56^{\text{s}}\text{.}08$
N.P.D.	$63^{\circ} 41' 53''$

agreeing precisely with Argelander (No. 2765 of *Bonner Sternverzeichniss*), declination $+26^{\circ}$, magnitude 9.5." Mr. Baxendell writes on the 21st, "It is probable that this star will turn out

the constellation of Corona Borealis. He describes the star as "very brilliant, of about the 2nd magnitude." Also Mr. Baxendell, of Manchester, wrote to one of us giving the observations which follow of the new star, as seen by him on the night of the 15th instant:

"A new star has suddenly burst forth in Corona. It is somewhat less than a degree distant from ϵ of that constellation in a south-easterly direction, and last night was fully equal in brilliancy to β Serpentis or ν Herculis, both stars of about the 3rd magnitude."

Last night, May 16, we observed this remarkable object. The star appeared to us considerably below the 3rd magnitude, but brighter than ϵ Coronæ. In the telescope it was surrounded with a faint nebulous haze, extending to a considerable distance, and gradually fading away at the boundary.* A comparative examination of neighbouring stars showed that this nebulosity really existed about the star. When the spectroscope was placed on the telescope, the light of this new star formed a spectrum unlike that of any celestial body which we have hitherto examined. The light of the star is compound, and has emanated from two different sources. Each light forms its own spectrum. In the instrument these spectra appear superposed. The principal spectrum is analogous to that of the sun, and is evidently formed by the light of an incandescent solid or liquid photosphere which has suffered absorption by the vapours of an envelope cooler than itself. The second spectrum consists of a few bright lines, which indicate that the light by which it is formed was emitted by matter in the state of luminous gas.† These spectra are represented with considerable approximate accuracy in a diagram which accompanies this paper.

Description of the Spectrum of Absorption.—In the red a little more refrangible than Fraunhofer's C are two strong dark lines. The interval between these and a line a little less refrangible than D is shaded by a number of fine lines very near each other. A less strongly marked line is seen about the place of solar D. Between D and a portion of the spectrum about the place of b of the solar spectrum, the lines of absorption are

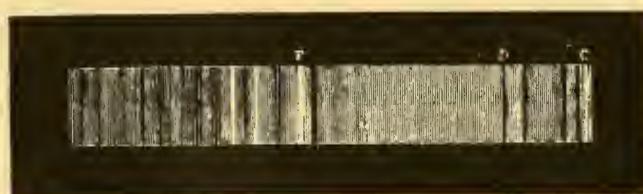
to be a variable of long or irregular period, and it may be conveniently at once designated T Coronæ." Sir John Herschel informs one of us that on June 9, 1842, he saw a star of the 6th magnitude in Corona very nearly in the place of this strange star. As Sir John Herschel's position was laid down merely by naked-eye allineations, the star seen by him may have been possibly a former temporary outburst of light in this remarkable object.

* On the 17th this nebulosity was suspected only; on the 19th and 21st it was not seen.

† The position of the groups of dark lines shows that the light of the photosphere, after passing through the absorbent atmosphere, is yellow. The light, however, of the green and blue bright lines makes up to some extent for the green and blue rays (of other refrangibilities) which have been stopped by absorption. To the eye, therefore, the star appears nearly white. However, as the star flickers, there may be noticed an occasional preponderance of yellow or blue. Mr. Baxendell, without knowing the results of prismatic analysis, describes the impression he received to be "as if the yellow of the star were seen through an overlying film of a blue tint."

numerous, but very thin and faint. A little beyond b commences a series of close groups of strong lines; these follow each other at small intervals, as far as the spectrum can be traced.

Description of the Gaseous Spectrum.—A bright line, much more brilliant than the part of the continuous spectrum upon which it falls, occupies a position which several measures make to be coincident with Fraunhofer's F.* At rather more than one-fourth of the distance which separates F and G, a second and less brilliant line was seen. Both these lines were narrow and sharply defined. Beyond these lines, and at a distance a little more than one-third of that which separates the second bright line from the strongest bright one, a third bright line was observed. The appearance of this line suggested that it was either double or undefined at the edges. In the more refrangible part of the spectrum, probably not far from G of the solar spectrum, glimpses were obtained of a fourth and faint bright line. At the extreme end of the visible part of the less refrangible end of the spectrum, about C, appeared a line brighter than the normal relative brilliancy of this part of the spectrum.



SPECTRUM OF ABSORPTION AND SPECTRUM OF BRIGHT LINES FORMING THE COMPOUND SPECTRUM OF A NEW STAR NEAR ϵ CORONÆ BOREALIS.

Fig. 28.

The brightness of this line, however, was not nearly so marked in proportion to that of the part of the spectrum where it occurs, as was that of the lines in the green and blue.†

General Conclusions.—It is difficult to imagine the present physical constitution of this remarkable object. There must be a photosphere of matter

* On the 17th the lines of hydrogen, produced by taking the induction-spark through the vapour of water, were compared in the instrument simultaneously with the bright lines of the star. The brightest line coincided with the middle of the expanded line of hydrogen which corresponds to Fraunhofer's F. On account of the faintness of the red end of the spectrum, when the amount of dispersion necessary for these observations was employed, the exact coincidence of the line in this part of the spectrum with the red line of hydrogen, though extremely probable, was not determined with equal certainty.

† The spectra of the star were observed again on the 17th, the 19th, the 21st, and the 23rd. On these evenings no important alteration had taken place. On the 17th and succeeding evenings, though the spectrum of the waning star was fainter than on the 16th, the red bright line appeared a little brighter relatively to the green and blue bright lines. On the 19th and 21st the absorption lines about b were stronger than on the 16th. From the 16th the continuous spectrum diminished in brightness more rapidly than the gaseous spectrum, so that on the 23rd, though the spectrum as a whole was faint, the bright lines were brilliant when compared with the continuous spectrum.

in the solid or liquid state emitting light of all refrangibilities. Surrounding this must exist also an atmosphere of cooler vapours, which give rise by absorption to the groups of dark lines.

Besides this constitution, which it possesses in common with the sun and the stars, there must exist the source of the gaseous spectrum. That this is not produced by the faint nebulosity seen about the star is evident by the brightness of the lines, and the circumstance that they do not extend in the instrument beyond the boundaries of the continuous spectrum. The gaseous mass from which this light emanates must be at a much higher temperature than the photosphere of the star; otherwise it would appear impossible to explain the great brilliancy of the lines compared with the corresponding parts of the continuous spectrum of the photosphere. The position of two of the bright lines suggests that this gas may consist chiefly of hydrogen.

If, however, hydrogen be really the source of some of the bright lines, the conditions under which the gas emits the light must be different from those to which it has been submitted in terrestrial observations; for it is well known that the line of hydrogen in the green is always fainter and more expanded than the brilliant red line which characterises the spectrum of this gas. On the other hand, the strong absorption indicated by the line F of the solar spectrum, and the still stronger corresponding lines in some stars, would indicate that under suitable conditions hydrogen may emit a strong luminous radiation of this refrangibility.*

The character of the spectrum of this star, taken together with its sudden outburst in brilliancy and its rapid decline in brightness, suggests to us the rather bold speculation that, in consequence of some vast convulsion taking place in this object, large quantities of gas have been evolved from it, that the hydrogen present is burning by combination with some other element and furnishes the light represented by the bright lines, also that the flaming gas has heated to vivid incandescence the solid matter of the photosphere. As the hydrogen becomes exhausted, all the phenomena diminish in intensity, and the star rapidly wanes.

In connection with this star, the observations which we made upon the spectra of α Orionis and β Pegasi, that they contain no absorption lines of hydrogen, appear to have some new interest.† The spectra of these stars agree in their general characters with the absorption spectrum of the new star. The whole class of white stars are distinguished by having hydrogen lines of extraordinary force. It may also be mentioned here that we have found that the spectra of several of the more remarkable of the variable stars, namely those

* On the dependence of the relative characters of the bright lines of hydrogen upon conditions of pressure and temperature, see Plücker and Hittorf, *Phil. Trans.*, 1865, p. 21.

† A little later the lines of hydrogen were detected in these stars; see p. 78.

distinguished by an orange or ruddy tint, possess a close general accordance with those of α Orionis, β Pegasi, and the absorption spectrum of the remarkable object described in this paper. The purely speculative idea presents itself from these observations, that hydrogen probably plays an important part in the differences of physical constitution which apparently separate the stars into groups, and possibly also in the changes by which these differences may be brought about.*

ON THE SPECTRUM OF THE STELLA NOVA VISIBLE ON THE GREAT NEBULA IN ANDROMEDA

(From *Report Brit. Assoc.*, 1885, p. 935)

THIS star appeared very near the position of greatest condensation in the Great Nebula in Andromeda. On the evening of September 3, it presented the appearance of an orange-coloured star of from the seventh to the eighth magnitude. When viewed in a spectroscope of small dispersive power, a continuous spectrum was seen which could be traced from about C in the red to a little beyond F. There was great brightness from about D to about *b*, which suggested strongly the presence of bright lines in that part of the spectrum. When a more powerful spectroscope was employed, the suspicion of some bright lines in this region was strengthened, but this point could not be certainly determined.

On September 9 the star was again observed. The colour of the star appeared less strongly orange. In the small spectroscope the great brightness about D was less marked, but the suspicion of bright lines in the region from D to *b* was confirmed; and the appearance of the spectrum in the large spectroscope left little doubt on my mind as to the existence of from three to five bright lines in this part of the spectrum.

* Mr. Baxendell sends us the following table of magnitudes:

	h	m	
May 15 at 12	o		G.M.T., T Coronæ = 3·6 or 3·7 magnitude.
" 16 "	10	30	" = 4·2
" 17 "	11	0	" = 4·9
" 18 "	12	30	" = 5·3
" 19 "	12	15	" = 5·7
" 20 "	12	0	" = 6·2
" 21 "	12	0	" = 7·3
" 22 "	11	15	" = 7·7
" 23 "	10	30	" = 7·9
" 24 "	10	30	" = 8·1

PRELIMINARY NOTE ON NOVA AURIGÆ

(From *Proc. Roy. Soc.*, vol. I., p. 465, 1892)

WE have delayed up to the present time presenting any account of our observations of Nova Aurigæ, in the constant hope that fine weather would enable us to make our observations more complete. We think now, however, that it may be of interest without further delay to send a short preliminary notice of this remarkable, and, in some respects, unprecedented, celestial phenomenon. For up to this time we have no record of a star in the spectrum of which the bright and dark lines of the same substances have been regarded as indicating respectively motions of approach and of recession of so great magnitude. It was partly for this reason that we were anxious for the opportunity of observing if any change in the amount of relative motion would show itself.

We received a telegram from Dr. Copeland in the early morning of the 2nd inst., and began our observations of the star on the night of the 2nd inst.

Perhaps the most noticeable feature to the eye in the star's spectrum was the great brilliancy of the hydrogen lines at C, F, and G; but the point of greatest interest was obviously that two of these lines, F and G,—and we have since observed the same with C—were accompanied each by a strong absorption line on the side towards the blue. Comparison with the lines of terrestrial hydrogen, while confirming the obvious presumption that the star-lines were really those of hydrogen, showed at once a large motion of recession of the bright lines and a motion of approach of a similar order of magnitude of the hydrogen which produced the absorption.

A photograph which we have since taken gives the star's spectrum as far in the ultra-violet as about $\lambda 3200$. On this plate we see not only the other hydrogen lines at *h* and H, but also the series beyond, which is characteristic of the white stars, bright, with dark absorption lines on the blue side.

Besides the hydrogen series there appear to be other lines doubled in a similar manner, including the sodium lines at D. The line K, which is at least as strongly impressed upon the plate as H, is not followed by so strong an absorption.

In the green part of the spectrum three very brilliant lines are seen on the red side of F. One of these falls not far from the position of the chief nebular line; but even when the shift of the spectrum is taken into account, we can scarcely regard this line as the true nebular line. In this connection it was a point of some importance to find that the strong and very characteristic line of the Orion nebula, which falls about $\lambda 3725$, is absent in our photograph of the Nova, also the strong line between α and β at about $\lambda 3868$.

[The third line from F is rather broad and resolvable into lines. It falls partly upon the more refrangible pair of the magnesium triplet at b, but its character and position do not permit us to ascribe it either to magnesium or carbon.—February 25.]

We wish to mention an early photograph of this star taken on the 3rd instant by Father Sidgreaves, at Stonyhurst, which we had the privilege of examining. This successful photograph extends from about λ to near D, and shows the remarkable doubling of many of the bright lines by dark ones, a feature which was at once noticed by Father Sidgreaves and ourselves.

In our photograph the spectrum of the star, which extends on the plate as far into the ultra-violet as our photographs of Sirius, is crowded throughout its entire length with dark and bright lines. In the visible region the number of bright lines and groups, including the double line of sodium, a fine line about the position of D₃, and lines on both sides of C, is also very great.

We prefer in this preliminary note not to enter into any more detailed discussion of the star's spectrum, nor to refer to the probable phenomena which may now be in progress in this celestial body. We reserve these considerations for the present.

ON NOVA AURIGÆ

(From *Proc. Roy. Soc.*, vol. li., p. 487, 1892)

WE had the honour in February last of communicating to the Royal Society a short preliminary note on the remarkable spectrum of this temporary star. We beg now to present a fuller account of our observations, together with two maps of the spectrum of this star, and some theoretical suggestions as to its nature. One map represents the result of our work by eye in the visible region; the other map has been drawn from a photograph of its spectrum, taken without its light having passed through glass, and which extends into the ultra-violet nearly as far as the absorption of our atmosphere permits even the solar rays to pass.

ON THE VISIBLE REGION OF THE STAR'S SPECTRUM

The kindness of Professor Copeland in sending us a special telegram on February 1 enabled us to commence our observations of the star on February 2, when it was of about the 4⁵th magnitude. These observations were continued on the following evening, and on February 5, 6, 22, and 24, and on March 15, 18, 19, 20, and 24, when the sky was more or less sufficiently clear for further observations to be made by eye. On the two ends of the spectrum

the observations were usually made with a spectroscope containing one dense prism of 60° , but the comparisons in the brighter parts of the spectrum were observed with a more powerful spectroscope containing two compound prisms.

Comparisons with Hydrogen.—Three bright lines of great brilliancy, about the positions H_α , H_β , and H_γ , left little doubt that they were due to hydrogen. The corresponding lines of a hydrogen vacuum tube were found to fall upon these lines, showing that they had their origin in this gas; but the line in the star at F, which could be best observed, showed a large shift of position towards the red. The line from the vacuum tube fell not upon the middle of the line, but near its more refrangible edge. The star line was brighter on the more refrangible side—so much so, indeed, that our first impression was that this side of the line only might be truly H_β , and the less bright part towards the red, a line of some other substance falling near it. Subsequent observations of the hydrogen lines in the star left no doubt that though they presented the unusual character of being double, and sometimes triple, they were due wholly to hydrogen. These lines were rather broad, but defined, especially so at the more refrangible edge. Similarly to what is observed in the spectrum of terrestrial hydrogen, C was narrower than F, which again was less broad than H_γ near G.

The remarkable phenomenon presented itself that all the bright hydrogen lines and some other of the bright lines were doubled by a dark line of absorption of the same gas on the blue side. The shift of the dark hydrogen lines towards the blue showed a velocity of approach of this cooler gas somewhat greater than the recession of the gas emitting the bright lines. Our estimates of the relative velocity would place it at about 550 miles a second, which is in good accordance with the result obtained by Professor Vogel from the measurement of his photographs.

So far as our instruments enabled us to determine the point under the unfavourable condition of the rapidly waning light of the star, no great change in the relative motion of the gases producing the bright and dark lines took place from February 2 to about March 7, when the star's light became too faint for such observations—a result which we believe to be in accordance with successive photographs taken at Potsdam, Cambridge (U.S.), Stonyhurst, and some other observatories.

Comparisons with Sodium.—A bright line, which on one occasion we glimpsed as double, appeared about the position of D.

Direct comparisons with a sodium flame, while leaving no doubt that the line was due to this substance, showed that it was shifted, similarly to the bright hydrogen lines, towards the red. Perhaps we should state that at the time we had the impression that this line was not shifted to so large an amount relatively to sodium as was the F line relatively to hydrogen. As the com-

parison was more difficult at this part of the spectrum, and one prism only was used, we do not attach importance to this observation.

Comparisons with Nitrogen and Lead.—There can be little doubt that one of the four brilliant lines in the green is the same line which appeared in the Nova of 1876, and was at that time suspected to be the chief nebular line. Very great pains were taken to ascertain its exact position and character.

For this purpose, on February 2, and again on February 3, direct comparisons were made with the more powerful spectroscope of the star's line with the brightest double line of the nitrogen spectrum, and also with a line of lead, to which line the near relative position of the nebular line is accurately known. Comparisons on both nights, and with both lines, showed that the star line was certainly less refrangible than the chief nebular line, and by a much larger amount than the shift of F relatively to hydrogen. A similar conclusion has been arrived at by Professor Young, Professor Vogel, Dr. Campbell at the Lick Observatory, Father Sidgreaves, Dr. Becker, and M. Bélopolsky at Pulkova. The position of the line in the star is about λ 5014, and the line may well be one about this position which is frequently seen bright at the Sun's limb.

It may be added that though three faint bright lines are to be seen in the star's spectrum, not far from the place of the second nebular line, no one of them can be regarded as that line. Indeed, no certain evidence exists that the chief nebular line occurs without the second line. In some cases of my early observations on the nebulae in which I recorded the spectrum as consisting of one line only, I have since, with better instruments, been able to see the second and the third lines as well. The origin of the second, as well as that of the chief nebular line, is not known. Professor Keeler has shown that the second nebular line is not coincident with the double line of iron, which is very near it.

The conclusion that the spectrum of the Nova has no relationship with that of the bright-line nebulae would be strengthened, if further confirmation were needed, by the absence in a photograph we took of the spectrum of the New Star of a very strong ultra-violet line which is usually found in the spectrum of the nebula of Orion.

Comparisons with the Hydrocarbon Flame and Carbon Oxide.—The brightest line in the spectrum of the Nova, with the exception of F, falls near the brightest edge of the green fluting of the hydrocarbon flame. Direct comparisons showed the star line to fall a little to the red side of the edge of the fluting; but, allowing for a shift of the star's spectrum, the place of the line would be near, though not coincident with, the brightest edge of the fluting.

The character of the star line leaves, however, no doubt on this point, for it is multiple with the brightest and most defined line on the blue side,

contrary to the fluting which is defined on the red side, and gradually falls off towards the blue. If any uncertainty could be supposed still to remain, it was wholly removed when we found no brightenings in the star's spectrum corresponding to the other flutings of the hydrocarbon flame. A bright band in the blue falls just beyond the fluting in this region. This band may have the same origin as a similar band in certain of the Wolf-Rayet stars.

We conclude that the spectrum of the Nova has no relationship with the usual spectrum of comets.

We found from direct comparison that the different set of flutings characteristic of the carbon oxide spectrum was not represented by any corresponding brightenings in the spectrum of the Nova.

Comparison with Magnesium.—It was not unreasonable to suppose that the star line might have its origin in magnesium, the triple line of which at b falls almost at the same place. The comparison showed the stellar line to fall upon the more refrangible pair of the magnesium triplet, and to overlap it slightly on both sides, but rather more on the blue side. Considering that with the resolving power used the three lines of the triplet were well separated, and that we sought in vain for a similar triplet in the star; and, further, that if the probable shift of the star's spectrum towards the red be taken into account, the star line would fall rather more to the blue side of the more refrangible pair of the triplet, we consider it probable that the star line has some other origin. The stellar line is multiple, but it was found difficult to observe it with a sufficiently narrow slit. A thin and defined bright line was clearly seen at the blue side of the rather broad stellar line, but the remaining and less bright part of the line was not certainly made out; on one occasion it was more than suspected of consisting of several lines.

We consider the evidence to be against the star line having its origin in magnesium, especially as no correspondingly bright lines were observed in the Nova at the positions of the other strong lines of the spark spectrum of magnesium, nor in our photograph at the position of the strong magnesium triplet a little more refrangible than H.

The third bright line in the green of the Nova which is nearest to F, and the least brilliant of the group of lines in this region, was found to have a wave-length of about $\lambda 4921$. A large number of bright lines were seen in the spectrum besides those which have been entered on the map (Plate 4).

The lines only of which we were able to fix the position with approximate accuracy are drawn across the spectrum. The places of the lines drawn partly across the map are from estimations only.

We observed a line a little more refrangible than D, of which the position when corrected for the shift of the spectrum, is at or very near that of D_3 . Also a bright line below C, and others between C and D.

On February 2 and February 3 groups of numerous bright lines crowded the spectrum between β and D, which were less easily seen as the star waned.

The continuous spectrum extended, when the star was brightest, below C, and as far into the blue as the eye could follow it—at this time to a little distance beyond G.

The visible spectrum of the Nova, and especially the reversal of H and K, and of the complete series of the hydrogen lines in the ultra-violet, together with the probable presence of D₃, suggest strongly a state of things not unlike what we find in the erupted matter at the solar surface. In a photograph of a prominence taken on March 4, 1892, which I have received from M. Deslandres, not only H and K and the complete series of hydrogen lines are reversed, but three bright lines appear beyond, which may be more refrangible members of the same series.*

Photograph of the Ultra-violet part of the Spectrum.—On February 22 and March 9 we took photographs of the star with a mirror of speculum metal and a spectroscope of which the optical part is made of Iceland spar and quartz.

The photograph taken on February 22 with an exposure of $1\frac{3}{4}$ hour surprised us in showing an extension of the star spectrum into the ultra-violet, almost as far as the limit imposed upon the light of celestial bodies by the absorption of our atmosphere.

Not only the hydrogen lines near G and at λ , but also H and K, together with the complete hydrogen series which appears dark in the white stars, came out bright, each with its corresponding absorption line on the blue side. There are some inequalities of brightness in these lines, especially in the line δ , which is brighter than γ or β , which probably arise from lines of other substances falling upon them. On this night K was followed by an absorption, which was less intense than the absorption at H.

Beyond the hydrogen series the spectrum is rich in bright lines, which, in most cases, are accompanied by lines of absorption. Necessarily, from the long range of spectrum included on the plate, the scale is small; and for this reason, and from the faintness of the more refrangible portion of the spectrum when observed under the measuring microscope, the positions given to the stronger groups, which alone have been inserted in the map, must be regarded as approximate only.

Below the spectrum of the Nova, the spectrum of Sirius has been placed for comparison. The group near the more refrangible limit of the spectrum †

* [M. Deslandres informs me that his measures of the positions of the three lines fall into Balmer's formula for the hydrogen series. We must regard them, doubtless, as members of that series and due to hydrogen.—June 10.]

† *Proc. Roy. Soc.*, vol. xlvi., p. 216.

has been drawn in. Numerous other lines between this group and the end of the hydrogen series have been detected in our photographs of Sirius, but have not yet been measured with sufficient accuracy to justify us in putting them into the map.

In this map no attempt has been made to show the shift of the spectrum of the Nova. The bright lines in the star have been put at the places of the hydrogen lines.

To the extreme limit of the spectrum a faint continuous spectrum shows itself.

The photograph of March 9, exposed for $1\frac{1}{2}$ hour, was rather faint, as the state of the sky was unfavourable.

The apparently Multiple Character of the Lines.—On February 2 we noticed that the F line was not uniform throughout its breadth, and soon came to the conclusion that it was divided, not quite symmetrically, by a very narrow dark line. The more refrangible component was brighter, and rather broader than the other. Later on in February, we were sure that small alterations were taking place in this line, and that the component on the blue side no longer maintained its superiority. We suspected, indeed, at times that the line was triple, and towards the end of February and in the beginning of March we had no longer any doubt that it was occasionally divided into three bright lines by the incoming of two very narrow dark lines.

Similar alterations, giving a more or less apparent multiple character to the lines, are to be seen not only in the bright lines, but also in those of absorption in contemporary photographs taken of the spectrum of the star. I may mention those taken at Potsdam, Stonyhurst, and the Lick Observatory. They were specially watched and measured by M. Bélopolsky at Pulkova.

Professor Pickering informs me that on a photograph taken at Cambridge, U.S., on February 27, H, K, and α are triple, and that Miss Maury recorded, "the dark hydrogen lines rendered double, and sometimes triple, by the appearance of fine bright threads superposed upon the dark bands."

To explain these appearances on the assumption that each component of the bright and dark lines is produced by the emission or absorption of hydrogen moving with a different velocity would require a complex system of six bodies all moving differently.

A much more reasonable explanation presents itself in the phenomena of reversal, which are very common on the erupted solar surface and in the laboratory.*

* [M. Deslandres permits me to quote the results of his recent observations on this point:—
"Lorsque l'on dirige sur la fente d'un spectroscope de grande dispersion l'image d'une facule du soleil on a invariablement avec les raies H et K du calcium un renversement triple. Même lorsque les facules sont larges et intenses, on obtient encore le renversement triple avec des raies brillantes centrales, plus faibles, il est vrai, si l'on envoie dans le spectroscope la lumiere de tous les points

Professor Liveing informs me that he and Professor Dewar, in their researches with the arc-crucible, met with cases in which, through the unequal expansion of the bright line on the two sides, the narrow reversed dark line did not fall upon the middle of the broader bright line, but divided it unsymmetrically. This effect was notably shown in photographs which they took of the spectrum of zinc. Unsymmetrical division of the lines by reversal would also come in, if the cooler and hotter portions of the gas were possessed of relative motion in the line of sight.

These observers met also with double reversals, which gave a triple character to the expanded single line. In one experiment, when sodium carbonate was introduced into the arc, the reversed D lines were seen as a broad dark band with a bright diffuse band in the middle. As the sodium evaporated the band narrowed, and the bright line in the middle showed a second reversal within it. This was a case of threefold reversal.

There would seem to be little doubt but that the more or less divided character—sometimes unsymmetrically—of the bright and dark lines of the Nova, which appeared to be undergoing continual alterations, was due to the incoming upon the broader lines of narrow reversed lines, bright or dark, as the case might be. Provision must therefore be made for conditions favourable for such reversals in any hypothesis which is suggested to account for the phenomena of the new star.

Waning of the Star.—The first record of this star was its appearance as a star of the 5th magnitude on a plate taken at Cambridge, U.S., on December 10, 1891. No star so bright as the 9th magnitude was found at its place on a plate taken by Dr. Max Wolf on December 8. Combining the photographic magnitudes obtained at Greenwich with the visual ones made at the University Observatory, Oxford, and by Mr. Stone and Mr. Knott, we find that throughout February and the first few days of March the light of the star declined very slowly, but with continual and considerable fluctuations, from about the 4·5th magnitude down to the 6th magnitude. After March 7, the remarkable swayings to and fro of the intensity of the light, set up probably by commotions attendant on the cause of its outburst, calmed down, and the star fell rapidly and with regularity to about the 11th magnitude by March 24, and then down to about 14·4th magnitude by April 1. On April 26, however, it was still visible at Harvard Observatory, magnitude 14·5, on the scale of the meridian photometer.

du soleil, comme c'est le cas pour les étoiles ; par exemple, en dirigeant le collimateur vers le soleil sans l'intermédiaire d'aucun objectif, ou encore en le dirigeant vers un point quelconque du ciel. Si les facules sont au centre la raie centrale est à sa place normale, si elles sont à l'est ou à l'ouest la raie centrale est déplacée légèrement (2 kil. au plus), mais déplacée sûrement. Au point de vue pratique cette propriété fournit un moyen de reconnaître l'état général de la surface solaire lorsque le soleil est caché par les nuages.”—June 20.]

We observed its spectrum for the last time on March 24, when it had fallen to nearly the 11th magnitude. We were still able to glimpse the chief features of its spectrum. The four bright lines in the green were distinctly seen, and appeared to retain their relative brightness; F the brightest, then the line near δ , followed by the lines about λ 5015 and λ 4921.

Traces of the continuous spectrum were still to be seen. Considering the much greater faintness of the continuous spectrum when the star was bright on February 2 than the brilliant lines falling upon it, we are not prepared to say that the falling off of the continuous spectrum was greater than might well be due to the waning of the star's light.

Professor Pickering informs me that on his plates "the principal bright lines faded in the order K, H, α , F, λ , and G, the latter line becoming much the brightest when the star was faint." The calcium lines K and H showed signs of variation during the whole time of the star's visibility, and I may remark that the order of the other lines agrees with the relative sensitiveness of the gelatine plate for these parts of the spectrum. Professor Pickering's photographic results appear to us to be in accordance with those we arrived at by eye, in not showing any material alteration in the nature of the star's light, notwithstanding its very large fall of intensity.

GENERAL CONCLUSIONS

Among the principal conditions which must be met by any theory put forward to account for the remarkable phenomena of the new star stands the persistence without any great alteration—though probably with small changes—of the large relative velocity of about 550 miles a second in the line of sight between the hydrogen which emitted the bright lines and the cooler hydrogen producing the dark lines of absorption.

If we assume two gaseous bodies, or bodies with gaseous atmospheres, moving away from each other after a near approach, in parabolic or hyperbolic orbits, with our Sun nearly in the axis of the orbits, the components of the motions of the two bodies in the line of sight, after they had swung round, might well be as rapid as those observed in the new star, and might continue for as long a time without any great change of relative velocity. Unfortunately information as to the motions of the bodies at the critical time is wanting, for the event through which the star became suddenly bright had been over for some forty days before any observations were made with the spectroscope.

Analogy from the variable stars of long period would suggest the view that the near approach of the two bodies may have been of the nature of a periodical disturbance, arising at long intervals in a complex system of bodies. Chandler has recently shown in the case of Algol that the minor irregularities

in the variation of its light are probably caused by the presence of one or more bodies in the system, besides the bright star and the dusky one which partially eclipses it. To a similar cause are probably due the minor irregularities which form so prominent a feature in the waxing and waning of the variable stars as a class. We know, too, that the stellar orbits are usually very eccentric. In the case of γ Virginis the eccentricity is as great as 0.9, and Auwers has recently found the very considerable eccentricity of 0.63 for Sirius.

The great relative velocity of the component stars of the Nova, however, seems to point rather to the casual near approach of bodies possessing previously considerable motion; unless we are willing to concede to them a mass very great as compared with that of the Sun. Such a near approach of two bodies of great size is very greatly less improbable than would be their actual collision. The phenomena of the new star, indeed, scarcely permit us to suppose even a partial collision; though if the bodies were very diffuse, or the approach close enough, there may have been possibly some mutual interpenetration and mingling of the rarer gases near their boundaries.

A more reasonable explanation of the phenomena, however, may be found in a view put forward many years ago by Klinkerfues, and recently developed by Wilsing, that under such circumstances of near approach enormous disturbances of a tidal nature would be set up, amounting, it may well be, to partial deformation in the case of gaseous bodies, and producing sufficiently great changes of pressure in the interior of the bodies to give rise to enormous eruptions of the hotter matter from within, immensely greater, but similar in kind, to solar eruptions; and accompanied probably by large electrical disturbances.

In such a state of things we should have conditions so favourable for the production of reversals undergoing continual change, similar to those exhibited by the bright and dark lines of the Nova, that we could not suppose them to be absent; while the integration of the light from all parts of the disturbed surfaces of the bodies would give breadth to the lines, and might account for the varying inequalities of brightness at the two sides of the lines.

The source of the light of the continuous spectrum, upon which were seen the dark lines of absorption shifted towards the blue, must have remained behind the cooler absorbing gas; indeed, must have formed with it the body which was approaching us, unless we assume that both bodies were moving exactly in the line of sight, or that the absorbing gases were of enormous extent.

The circumstance that the receding body emitted bright lines, while the one approaching us gave a continuous spectrum with broad absorption lines similar to a white star, may, perhaps, be accounted for by the two bodies being

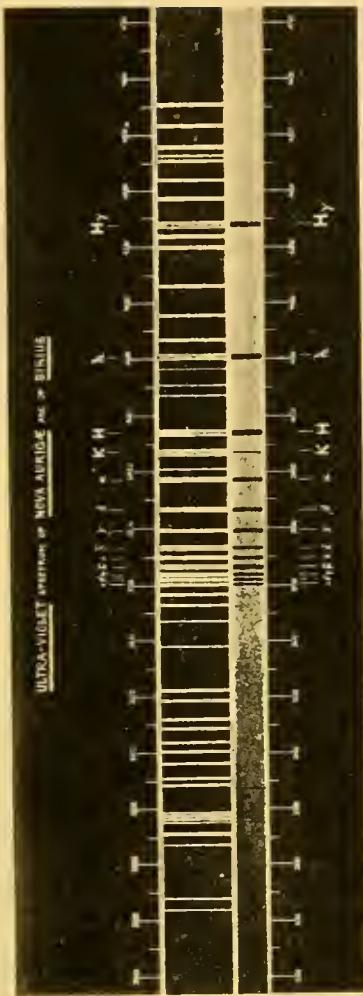


Fig. 29.

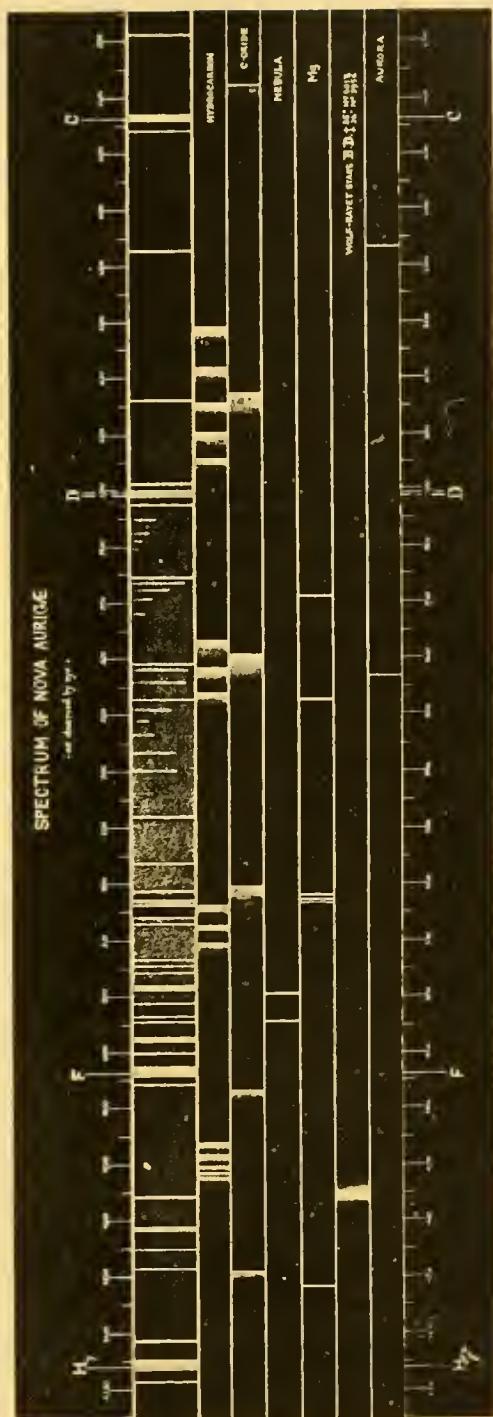


Fig. 30.

in different evolutionary stages, and consequently differing in diffuseness and in temperature. Indeed in the variable star β Lyræ, we have probably a binary system, of which one component gives bright lines, and the other dark lines of absorption. We must, however, assume a similar chemical nature for both bodies, and that they existed under conditions sufficiently similar for equivalent dark and bright lines to appear in their respective spectra.

We have no knowledge of the distance of the Nova, but the assumption is not an improbable one that its distance was of the same order of greatness as that of the Nova of 1876, for which Sir Robert Ball failed to detect any parallax. In this case, the light-emission suddenly set up, certainly within two days and possibly within a few hours, was probably much greater than that of our Sun; yet within some fifty days after it had been discovered, at the end of January, its light fell to about $\frac{1}{30}$ th part, and in some three months to nearly the $\frac{1}{10000}$ th part. As long as its spectrum could be observed the chief lines remained without material alteration of relative brightness. Under what conditions could we suppose the Sun to cool down sufficiently for its light to decrease to a similar extent in so short a time, and without the incoming of material changes in its spectrum? It is scarcely conceivable that we can have to do with the conversion of gravitational energy into light and heat. On the theory we have ventured to suggest, the rapid calming down, after some swayings to and fro of the tidal disturbances, and the closing in again of the outer and cooler gases, together with the want of transparency which might come in under such circumstances, as the bodies separated, might account reasonably for the very rapid and at first curiously fluctuating waning of the Nova; and also for the observed absence of change in its spectrum.

I may, perhaps, be permitted to remark that the view suggested by Dr. William Allen Miller and myself, in the case of the Nova of 1866,* was essentially similar, in so far as we ascribed it to erupted gases. The great suddenness of the outburst of that star, within a few hours probably, and the rapid waning from the 3·6 magnitude to the 8·1 magnitude in nine days, induced us to throw out the additional suggestion that possibly chemical actions between the erupted gases and the outer atmosphere of the star may have contributed to its sudden and transient splendour.

ON THE BRIGHT BANDS IN THE PRESENT SPECTRUM OF NOVA AURIGÆ

(From *Proc. Roy. Soc.*, vol. liv., p. 30, 1893)

SOME few prefatory words are called for in explanation of the partial incompleteness of the present communication.

* *Proc. Roy. Soc.*, vol. xv., p. 146.

A considerable brightening, from below the 14th magnitude to above the 10th magnitude, was found to have taken place in the Nova when it was re-observed in the early part of August 1892, and to be accompanied by a modification of its spectrum, apparently analogous to a similar change in the spectrum of Nova Cygni in 1877, since the observations we made of the star on March 24, 1892, when it had fallen to nearly the 11th magnitude.*

In consequence, however, of the removal of the eye-end of the telescope to the workshops of Messrs. Troughton & Simms for the attachment to it of the mounting for a fine Rowland grating by Mr. Brashear, we were without the means of observing the star and its spectrum during the whole of the autumn and the early winter. It was not until the beginning of the year that the new spectroscope was mounted in our observatory, and then, from some instrumental causes of delay and from a prevalence of bad weather, we were not able to observe the spectrum of the Nova until the night of February 1.

Before this time the altered appearance of the spectrum of the Nova had been observed at several observatories, and its spectrum had been described as consisting mainly, in the visible region, of a bright line in the orange, of the two nebular lines, and of the hydrogen line at F.

As soon as we directed the spectroscope to the star, we saw at once, even with one prism, that the two principal bright bands which had been described as the "nebular lines" were, in strong contrast with these, not single lines but broad bright spaces, diffused at the ends and irregularly bright, which we suspected to be groups of bright lines.

On February 8 we observed these bright spaces with the 4-inch grating of 14,438 lines to the inch, using the spectrum of the second order. The collimator and the telescope have each an aperture of 2 inches, and the spectrum was viewed under a magnifying power of 23 diameters. Our suspicion was then confirmed, the bands being clearly resolved into groups of bright lines upon a feebly luminous background.

On February 26, micrometric measures were begun of the positions of the constituent lines of the groups, when unfortunately we discovered that in consequence of flexure in one part of the instrument, a shifting of the micrometer webs relatively to the lines of the spectrum was liable to take place, and so make the measures uncertain to about as much as 2 tenth-metres when the spectrum of the second order was in use.

The cause of the want of rigidity of the instrument in this respect made it necessary that the spectroscope should go back to Messrs. Troughton & Simms' workshops; and then, from unavoidable delays and the coming in of the Easter holidays, it was not until the second week in April that the spectroscope was again in position for use; but by this time the Nova was

* *Proc. Roy. Soc.*, vol. li., p. 492.

too far past the meridian for satisfactory observations to be made upon its spectrum.

Our opportunities of working upon the spectrum of the star were thus absolutely restricted to the few fine nights between February 1 and February 26; and, further, our observations of the positions of the lines are, for the reason we have mentioned, affected with a possibility of error which may be as great as 2 tenth-metres, though it is probable that the positions given in the diagram are not actually in error to as much as half that amount.

For the same reason the resolution of the minor features of the groups has not been worked out with the completeness which was well within our instrumental means, if the number of fine nights had not been so limited; for on some of the nights on which observations were attempted the sky was not clear enough from thin haze for the resolution of the more difficult features of the spectrum of a star of between the 9th and 10th magnitude.

Still, notwithstanding the comparatively incomplete state of our observations, which we greatly regret, we do not hesitate to consider them of sufficient importance, bearing as they do upon so remarkable a phenomenon as would be the change of a star into a nebula, to justify us in communicating them to the Royal Society.

The spectroscope is provided with a 4-inch Rowland grating by Brashear, and a prism of dense flint of 27° , silvered on one face, which can take the place of the grating in the grating box.

As we have already stated, the observation of the Nova with this prism showed the bright "lines" broad and irregularly bright, and raised the suspicion in our minds that they were probably groups. They were observed more or less successfully with the grating, usually with an eyepiece magnifying 23 diameters, on February 8, 10, 11, 16, 17, and 26.

1. BRIGHTER GROUP NEAR THE POSITION OF THE PRINCIPAL NEBULAR LINE

The separate results of our more favourable observations of this group on the different nights are put together in the accompanying diagram. In addition, however, to the details drawn in the diagram, at several very favourable moments of seeing, we had distinct and undoubted glimpses of finer lines in the spaces between the brighter ones, of which some only are given in the diagram. For this reason the diagram must be regarded as an incomplete representation of the group, though showing accurately its main features and general character.

The group, as shown in the diagram, extends through a little more than 15 tenth-metres, and consists of lines more or less bright upon a feebly luminous background, which can be traced to some distance beyond the lines at both

ends of the group. The more prominent features are : two lines, the brightest in the group and about equally bright—but the more refrangible one rather the brighter—which form the termination of the group towards the blue ; a line nearly as bright about the middle of the group ; and a third prominent line at the end of the group towards the red.

We have little doubt, though we hesitate to state it positively, that the space between the two brightest lines, that on the blue side of the bright line in the middle of the group and the spaces on the blue sides of some others of the lines, were darker than the faint luminous background, in which case we should have to do possibly with lines of absorption of the same substances shifted towards the blue. A few only of the finer bright lines which were occasionally glimpsed between the more brilliant lines have been put into the diagram.

The pair of bright lines at the termination of the group towards the blue

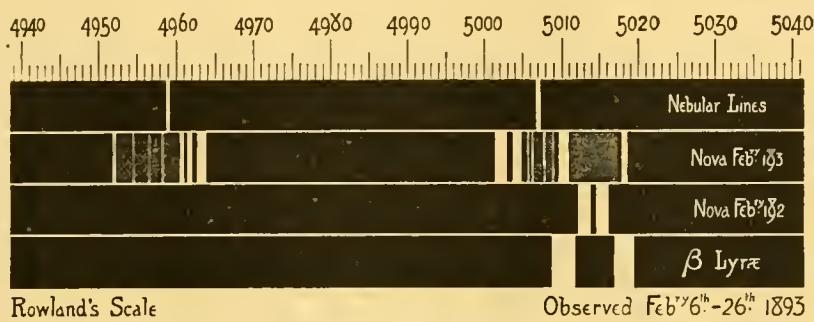


Fig. 31.

makes this the brighter end of the group, which does not, however, as a whole possess any of the usual features of a fluting.

On February 10, the micrometer webs were placed so as just to include the bright lines of the group, but not the faint background, which at the clearest moments could be traced for some distance, especially at the blue end of the group. The instrument remained untouched, and the position given in the diagram is that found from the places of the micrometer webs upon the solar spectrum, on Rowland's scale, as observed on the following morning.

On the 26th, measures of this group were made relatively to the position of the principal line in the nebula of Orion ; these gave also almost exactly the same position in the spectrum for the group ; but, as we have already stated, all these measures are unfortunately liable to a small error from the possible flexure, at that time, of a part of the instrument.

The mean of Mr. Campbell's measures at the Lick Observatory, during the period of our observations, from February 10 to February 27, gives λ 5006 for the middle of the band. He remarks : "In any discussion of these observa-

tions it is necessary to take into account the difficulty of accurately locating the centre of a line so broad and diffuse as this one is."*

In another place Mr. Campbell says: "The line is at least 8 tenth-metres broad and the edges very diffuse."†

These observations would be brought into accordance with our own, so far as relates to the length and position of the band, if we suppose Mr. Campbell to have observed only the more refrangible and much brighter half of the whole group.‡

The probable analogy between the Nova and the remarkable variable star β Lyræ, in the spectrum of which also we have to do apparently with bright and dark lines of the same substances, though not in all cases identical with those of the Nova, in motion relatively to each other, which we ventured to point out in our former communication on the Nova,§ has been recently greatly strengthened by the photographic observations of β Lyræ at different stages of its periodic variations by Dr. Bélopolsky at the Observatory of Pulkova.

In some of his photographs, especially in one taken shortly after the star's second maximum, bright lines come out near the positions of the bright groups of the Nova which are now under discussion. As the scale of Dr. Bélopolsky's photographs is much smaller than that of our diagram, we felt some hesitation in attempting any identification of his lines with those of the Nova. At our request, Dr. Bélopolsky has been so kind as to put into our diagram the two brightest of the lines of β Lyræ, as they appeared shortly after the second maximum, which fall within the brightest group of the Nova, and which, indeed, may be identical with two of the lines in the Nova. It may, however, be thought that the lines of β Lyræ suggest that they are independent bright lines rather than members of a group such as that of the Nova.

Whatever may ultimately be found to be the truth, there can be no question as to the probable high significance of the remarkable analogy which exists between the changes which take place in β Lyræ and those which have been observed in Nova Aurigæ.

The two other spectra in the diagram represent respectively the position and character of the two nebular lines, and the position of the bright double or multiple band which was so brilliant in this region of the Nova in the beginning of last year.

* *Astronomy and Astro-Physics*, May 1893, pp. 418, 419.

† *Publ. Ast. Soc. Pacific*, vol. iv., p. 246.

‡ Professor Campbell also says: "On August 30 the line was suspected to be double, and the grating measures of that night refer to a point midway between the two condensations. On September 7 the measures refer to a point of maximum brightness slightly less refrangible than the centre of the line" (*Astronomy and Astro-Physics*, Oct. 1892, p. 718).

§ *Proc. Roy. Soc.*, vol. li., p. 494.

2. BRIGHT GROUP NEAR THE POSITION OF THE SECOND NEBULAR LINE

Not anticipating that our opportunities of observing were to be so soon cut off, we gave our attention chiefly to the brighter group, intending, after we had completed our observations and measures of it, to attack seriously the second group.

However, on nearly all the nights we observed we gave some attention to this group, which, from being fainter, is more difficult to resolve, though on the clearer nights it was fairly well seen with the grating.

Generally, the group may be described as of the same order as the brighter one, consisting of bright lines and possibly of some absorption lines upon a feebly illuminated background.

We have endeavoured to represent in the diagram as truthfully as we can the best views we obtained of this group; but during one or two exceptional moments of good seeing we thought that we glimpsed finer bright lines in the spaces between. Indeed, the group may consist of a close grouping of bright lines.

For the same reasons, fewer measures were attempted of this group, and its position was less accurately determined; but neither the constitution of the group as represented in the diagram nor its position can, we think, be much in error.

We were also unable to work upon the bright line in the orange, and to do more than satisfy ourselves, by a direct comparison, that the line about F was really the hydrogen line in that region.

GENERAL CONCLUSIONS

It need scarcely be said that no contrast could well be more striking than that which these extended groups of lines form with the two narrow and defined lines in the spectrum of the Great Nebula in Orion.

It is difficult to suppose that we have to do with the same substance or substances, whatever they may be, which produce the nebular lines, even if we imagine very different conditions of temperature, or even allotropic conditions.

In the laboratory, allotropic changes are not usually accompanied by new groups, or lines at the positions of the characteristic lines of the substances in their original state.

We wish to speak at present with great reserve, as our knowledge of the Nova is very incomplete, but we do not regard the circumstance that the two groups of lines above described fall near the positions of the two principal nebular lines as sufficient to show any connection between the present physical state of the Nova and that of a nebula of the class which gives these lines.

Influenced by the analogy between some of the changes in the spectrum of the Nova and those which are associated in the spectrum of β Lyrae with the variation of its light, and also by other reasons which we pointed out in our former communication, we are still strongly inclined to take the same view which we there ventured to suggest—namely, that in the outburst of the Nova we have not to do mainly with cold matter raised suddenly to a high temperature by a collision of any form, but rather, for the most part, as was suggested by Dr. Miller and myself in 1866 in the case of the first temporary star examined with the spectroscope, with an outburst of existing hot matter from the interior of the star or stars; indeed, with phenomena broadly similar to, but on an immensely grander scale than, those with which we are familiar in the periodic greater and lesser disturbances of the sun's surface.

Such grand eruptions may well be expected to take place as stars cool, and if in two or more dull and comparatively cool stars such a state of things were imminent, then the tidal action due to their near approach might be amply adequate to determine, as by a trigger action, such eruptions.

Under such conditions, fluctuations of brightness and subsequent partial renewals of the eruptive disturbances might well take place.

Section VI
SPECTRA OF COMETS

LIST OF PAPERS

“On the Spectrum of Comet I, 1866.”
Proc. Roy. Soc., vol. xv., p. 5. P. 267.

“On the Spectrum of Comet II, 1867.”
Month. Not., vol. xxvii., p. 288. (Abstract.) P. 270.

“On the Spectrum of Comet II, 1868.”
Proc. Roy. Soc., vol. xvi., p. 481. (Abstract.) See p. 273.

“On the Spectrum of Brorsen’s Comet, 1868.”
Proc. Roy. Soc., vol. xvi., p. 386. P. 270.

“Further Observations on the Spectra of some of the Stars and Nebulæ,
with an attempt to determine therefrom whether these Bodies
are moving towards or from the Earth; also Observations on the
Spectra of the Sun and of Comet II, 1868.”
Phil. Trans., 1868, vol. clviii., p. 529. P. 273.

“On the Spectrum Observations of Comets.”
Phil. Mag., vol. xxxvii., p. 456.

“On the Spectrum of Uranus and of Comet I, 1871.”
Proc. Roy. Soc., vol. xix., p. 488. P. 284.

“On the Spectrum of Encke’s Comet, 1871.”
Proc. Roy. Soc., vol. xx., p. 45. P. 284.

“On the Telescopic Appearance of Encke’s Comet, 1871.”
Proc. Roy. Soc., vol. xx., p. 87. P. 287.

- "On the Spectrum of Coggia's Comet."
Proc. Roy. Soc., vol. xxiii., p. 154. 1874. P. 288.
- "Note on the Photographic Spectrum of Comet *b*, 1881."
Proc. Roy. Soc., vol. xxxiii., p. 1. P. 295.
- "On the Photographic Spectrum of Comet I (Wells), 1882."
Proc. Roy. Soc., vol. xxxiv., p. 148. P. 297.
- "On Comets." (Lecture.)
Proc. Roy. Inst., vol. x., p. 1. Jan. 1882.

HISTORICAL STATEMENT

(From *The Nineteenth Century Review*, June 1897)

COMETS in the olden times were looked upon as the portents of all kinds of woe :

"There with long bloody haire, a Blazing Star
Threatens the World with Famin, Plague, and War:
To Princes, death: to Kingdoms, many crosses:
To ali Estates, ineuitable Losses:
To Heard-men, Rot: to Plough-men, hap-lesse Seasons:
To Saylers, Storms: to Cities, ciuill Treasons."*

Though they were no longer, at the time of which I am speaking, a terror to mankind, they were a great mystery. Perhaps of no other phenomenon of nature had so many guesses at truth been made on different, and even on opposing, principles of explanation. It was about this time that a beam of light was thrown in, for the first time, upon the night of mystery in which they moved and had their being, by the researches of Newton of Yale College, by Adams, and by Schiaparelli. The unexpected fact came out of the close relationship of the orbits of certain comets with those of periodic meteor-swarms. Only a year before the observations of which I am about to speak were made, Odling had lighted up the theatre of the Royal Institution with gas brought by a meteorite from celestial space. Two years earlier Donati showed the light of a small comet to be in part self-emitted, and so not wholly reflected sunshine.

I had myself, in the case of three faint comets—in 1866, in 1867, and January 1868—discovered that part of their light was peculiar to them, and that the light of the last one consisted mainly of three bright flutings. Intense, therefore, was the great expectancy with which I directed the telescope with its attached spectroscope to the much brighter comet which appeared in June 1868.

The comet's light was resolved into a spectrum of three bright bands or flutings, each alike falling off in brightness on the more refrangible side. On

* Du Bartas, translated by J. Sylvester, fol. 1621, p. 33.

the evening of the 22nd I measured the positions in the spectrum of the brighter beginnings of the flutings on the red side. I was not a little surprised the next morning to find that the three cometary flutings agreed in position with three similar flutings in the brightest part of the spectrum of carbon. Some time before, I had mapped down the spectrum of carbon, from different sources, chiefly from different hydrocarbons. In some of these spectra, the separate lines of which the flutings are built up are individually more distinct than in others. The comet bands, as I had seen them on the previous evening, appeared to be identical in character in this respect, as well as in position in the spectrum, with the flutings as they appeared when I took the spark in a current of olefiant gas. I immediately filled a small holder with this gas, arranged an apparatus in such a manner that the gas could be attached to the end of the telescope, and its spectrum, when a spark was taken in it, seen side by side with that of the comet.

Fortunately the evening was fine ; and on account of the exceptional interest of confronting for the first time the spectrum of an earthly gas with that of a comet's light, I invited Dr. Miller to come and make the crucial observation with me. The expectation which I had formed from my measures was fully confirmed. The comet's spectrum when seen together with that from the gas agreed in all respects precisely with it. The comet, though "subtle as Sphinx," had at last yielded up its secret. The principal part of its light was emitted by luminous vapour of carbon.

This result was in harmony with the nature of the gas found occluded in meteorites. Odling had found carbonic oxide as well as hydrogen in his meteorite. Wright, experimenting with another type of meteorite, found that carbon dioxide was chiefly given off. Many meteorites contain a large percentage of hydrocarbons ; from one of such sky-stones a little later I observed a spectrum similar to that of the comet. The three bands may be seen in the base of a candle flame.

Since these early observations the spectra of many comets have been examined by many observers. The close general agreement as to the three bright flutings which form the main feature of the cometary spectrum confirms beyond doubt the view that the greater part of the light of comets is due to the fluted spectrum of carbon. Some additional knowledge of the spectra of comets, obtained by means of photography, will have its proper place later on.

In 1881, for the first time since the spectroscope and also suitable photographic plates had been in the hands of astronomers, the coming of a bright comet made it possible to extend the examination of its light into the invisible region of the spectrum at the blue end. On June 22, by leaving very early a banquet at the Mansion House, I was able, after my return home, to obtain,

with an exposure of one hour, a good photograph of the head of the comet. It was under a great tension of expectancy that the plate was developed, so that I might be able to look for the first time into a virgin region of nature, as yet unexplored by the eye of man.

The plate contained an extension and confirmation of my earlier observations by eye. There were the combined spectra of two kinds of light—a faint continuous spectrum, crossed by Fraunhofer lines which showed it to be reflected solar light. Upon this was seen a second spectrum of the original light emitted by the comet itself. This spectrum consisted mainly of two groups of bright lines, characteristic of the spectra of certain compounds of carbon. It will be remembered that my earlier observations revealed the three principal flutings of carbon as the main feature of a comet's spectrum in the visible region. The photograph brought a new fact to light. Liveing and Dewar had shown that one of these bands consisted of lines belonging to a nitrogen compound of carbon. We gained the new knowledge that nitrogen, as well as carbon and hydrogen, exists in comets. Now, nitrogen is present in the gas found occluded in some meteorites. At a later date, Dr. Flight showed that nitrogen formed as much as 17 per cent. of the occluded gas from the meteorite of Cranbourne, Australia.

SPECTRUM OF COMET I, 1866

(*Proc. Roy. Soc.*, vol. xv., p. 5, 1866)

THE successful application of prismatic analysis to the light of the nebulæ showed the great importance of subjecting the light of comets to a similar examination, especially as we possess no certain knowledge of the intimate nature of those singular and enigmatical bodies, or of the cosmical relations which they sustain to our system. The importance of a prismatic analysis of cometary light is enhanced by the consideration of the general resemblance which some of the nebulæ present to the nearly round vaporous masses of which some comets, in some positions at least in their orbits, appear to consist—a resemblance which suggests the possible existence of a close relation between nebulous and cometary matter.

I made several unsuccessful attempts to obtain a prismatic observation of Comet I, 1864. The position of the comet and the weather were unfavourable. M. Donati succeeded in making an examination of the spectrum of this comet. "It resembles," says M. Donati, "the spectra of the metals; in fact, the dark portions are broader than those which are more luminous, and we may say these spectra are composed of three bright lines."*

* *Monthly Notices R.A.S.*, vol. xxv., p. 114.

Yesterday evening, January 9, 1866, I observed the spectrum of Comet I, 1866. The telescope and spectrum-apparatus which I employed are described in my paper "On the Spectra of some of the Nebulæ."

The appearance of this comet in the telescope was that of an oval nebulous mass surrounding a very minute and not very bright nucleus. The length of the slit of the spectrum-apparatus was greater than the diameter of the telescopic image of the comet.

The appearance presented in the instrument when the centre of the comet was brought nearly upon the middle of the slit was that of a broad continuous spectrum fading away gradually at both edges. These fainter parts of the spectrum corresponded to the more diffused marginal portions of the comet. Nearly in the middle of this broad and faint spectrum, and in a position in the spectrum about midway between b and F of the solar spectrum, a bright point was seen. The absence of breadth of this bright point in a direction at right angles to that of the dispersion showed that this monochromatic light was emitted from an object possessing no sensible magnitude in the telescope.

This observation gives us the information that the light of the coma of this comet is different from that of the minute nucleus. The nucleus is self-luminous, and the matter of which it consists is in the state of ignited gas. As we cannot suppose the coma to consist of incandescent solid matter, the continuous spectrum of its light probably indicates that it shines by reflected solar light.

Since the spectrum of the light of the coma is unlike that which characterises the light emitted by the nucleus, it is evident that the nucleus is not the source of the light by which the coma is rendered visible to us. It does not seem probable that matter in the state of extreme tenuity and diffusion in which we know the material of the comæ and tails of comets to be, could retain the degree of heat necessary for the incandescence of solid or liquid matter within them. We must conclude, therefore, that the coma of this comet reflects light received from without; and the only available foreign source of light is the sun.* If a very bright comet were to visit our system it might be possible to observe whether the spectra of the coma and the tail contain the dark lines which distinguish solar light. If the continuous spectrum of the coma of Comet I, 1866, be interpreted to indicate that it shines by reflecting solar light, then the prism gives no information of the state of the matter which forms the coma, whether it be solid, liquid, or gaseous. Terrestrial

* This conclusion is in accordance with the results of observations on the polarisation of the light of the tails of some comets. Some of these observations appear to have been made with the necessary care. See J. P. Bond's "Account of the Great Comet of 1858," *Annals of the Astronomical Observatory of Harvard College*, vol. iii., pp. 305-10.

phenomena would suggest that the parts of a comet which are bright by reflecting the sun's light are probably in the condition of fog or cloud.

We know, from observation, that the comæ and tails of comets are formed from the matter contained in the nucleus.

The usual order of the phenomena which attend the formation of a tail appears to be that, as the comet approaches the sun, material is thrown off, at intervals, from the nucleus in the direction towards the sun. This material is not at once driven into the tail, but usually forms in front of the nucleus a dense luminous cloud, into which for a time the bright matter of the nucleus continues to stream. In this way a succession of envelopes may be formed, the material of which afterwards is dissipated in a direction opposite to the sun, and forms the tail. Between these envelopes dark places are usually seen.

If the matter of the nucleus is capable of forming by condensation a cloud-like mass, there must be an intermediate state in which the matter ceases to be self-luminous, but yet retains its gaseous state, and reflects but little light. Such a non-luminous and transparent condition of the cometary matter may possibly be represented by some at least of the dark spaces which, in some comets, separate the cloud-like envelopes from the nucleus and from each other.

Several of the nebulae which I have examined give a spectrum of one line only, corresponding in refrangibility with the bright line of the nucleus of the comet referred to in this paper. Other nebulae give one or two fainter lines besides this bright line. Whether either or both of these were also present in the spectrum of this comet I was unable to determine. The light of the comet was feeble, and the presence of the continuous spectrum made the detection of these lines more difficult. I suspected the existence of the brighter of these lines. I employed different eyepieces, and also gave breadth to the bright point by the use of the cylindrical lens, but I was not able to obtain satisfactory evidence of more lines than the bright one already described.

In my paper "On the Spectra of the Nebulae" I showed that this bright line corresponds in refrangibility with the brightest of the lines of nitrogen. This line may perhaps be interpreted as an indication that cometary matter consists chiefly of nitrogen, or of a more elementary substance existing in nitrogen.*

The great varieties of structure which may exist among comets, as well as the remarkable changes which the same comet undergoes at different epochs, will cause all those who are interested in the advance of our knowledge of the cosmical relations of these bodies, and of the gaseous nebulae, to wait with some impatience the visit of a comet of sufficient splendour to permit a satisfactory prismatic examination of the physical state of cometary matter

* This view was not supported by later observations. See pp. 185, 186.

during the various changes which are dependent upon the perihelion passage of the comet.

ON THE SPECTRUM OF COMET II, 1867

(*Monthly Notices, vol. xxvii., p. 288, 1867*)

ABSTRACT

A continuous spectrum was formed by the light of the coma. Once or twice I suspected the presence of two or three bright lines in the spectrum of the faint nucleus.

ON THE SPECTRUM OF BRORSEN'S COMET, 1868

(From *Proc. Roy. Soc., vol. xvi., p. 386, 1868*)

IN January 1866 I communicated to the Royal Society the result of an examination of a small comet visible in the beginning of that year.* I examined the spectrum of another small and faint comet in May 1867. The spectra of these objects, as far as their very feeble light permitted them to be observed, appeared to be very similar. In the case of each of these comets, the spectrum of the minute nucleus appeared to consist of a bright line between *b* and *F*, about the position of the double line of the spectrum of nitrogen, while the nebulosity surrounding the nucleus and forming the coma gave a spectrum which was apparently continuous.

Unfavourable weather prevented me from obtaining an observation of Brorsen's comet, at its present reappearance, before April 29. Since that evening I have examined it on May 2, 4, 6, 7, 12, 13. As I have not noticed any change in its spectrum during this time, I will put together the results of my observations on different nights, in order to avoid the repetition which would occur if the observations were arranged in the order in which they were made.

I tried various spectrosopes upon this object. The best views of its spectrum were obtained with a spectroscope of the form already described in my former papers,† and furnished with one prism of very dispersive flint-glass, with a refracting angle of 60° . Some measures were taken with a similar spectroscope, with two prisms of 60° .

The comet appears in the telescope as a nearly round nebulosity, in which the light increases rapidly towards the centre, where on some occasions I detected, I believe, a small stellar nucleus. Generally this minute nucleus was

* *Proc. Roy. Soc., vol. xv., p. 5.*

† *Phil. Trans., 1864, p. 415.*

not to be distinguished from the bright central part of the comet. I suspected two or three bright points in the coma. On May 7 I perceived a small extension of the faint surrounding nebulosity in a direction opposite to the sun, so as to form a short tail.

The spectrum of this comet consists for the most part of three bright bands. The width of the bands in the instrument shows that they are not due alone to the stellar nucleus, but are produced by the light of the brighter portions of the coma.

I took some pains to learn the precise character of these luminous bands. When the slit was wide they resembled the expanded lines seen in some gases: for example, the line F in the spectrum of hydrogen at the atmospheric pressure. As the slit was made narrow, the two fainter bands, namely the

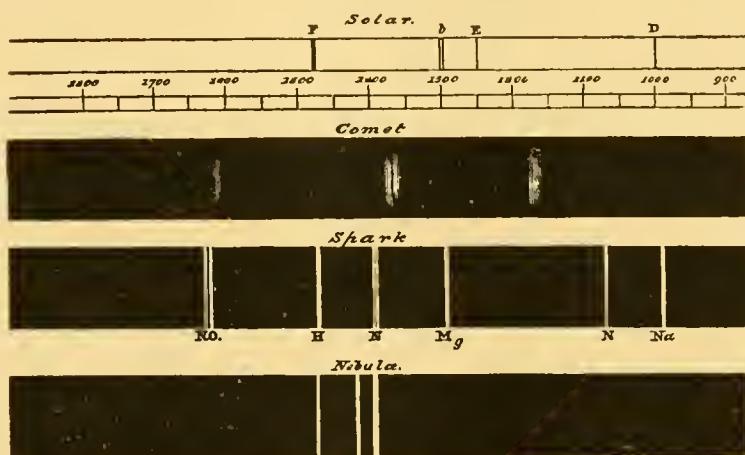


Fig. 32.

one in the yellow and the one in the blue, appeared to fade out without becoming more defined. I was unable to resolve these bands into lines. In this respect they are very different from the bright lines of the nebulae, which become narrow as the slit is made narrow.

The middle band, which is so much brighter than the others that it may be considered to represent probably three-fourths, or nearly so, of the whole of the light which we receive from the comet, appears to possess similar characters. In this nebulous band, however, I detected occasionally two bright lines, which appeared to be shorter than the band, and may be due to the nucleus itself. This suspicion seems to be strengthened by the circumstance that, when by moving the telescope the image of the comet was made to pass before the slit, these brighter lines were only observed when the middle of the comet was upon the slit, while the nebulous band continued as long as any part of the comet, except its extreme margin, was upon the slit.

Besides these three bright bands there was a very faint continuous spectrum. This spectrum is omitted in the diagram, as it could scarcely be represented without making it appear too strong relatively to the bright bands.

The position in the spectrum of the bands was determined by micro-metrical measures, and also by simultaneous comparison, of the bands with the bright lines of magnesium, sodium, hydrogen, and nitrogen. The brightest band, which is in the green part of the spectrum, is nearly in the position of the brightest line of the nebulae, which coincides with the double line of the spectrum of nitrogen; but, as the diagram shows, the band in the comet is in a small degree less refrangible than the line of nitrogen. This difference of refrangibility cannot be attributed to the comet's motion, since at the time the observations were made the comet was approaching the earth.

The band in the blue is considerably more refrangible than F, and is nearly as refrangible as the group of bright lines in the air-spectrum, which have the numbers 2642, 2669 in the map and tables of my paper "On the Spectra of the Chemical Elements."*

The least refrangible of the bands occurs in the yellow part of the spectrum, at about the distance from E of one-third of the interval which separates E from D.

The spectrum of this comet resembles the diagram given by Donati of the spectrum of Comet I, 1864.† The positions of the three bands seen by him appear to agree with those which the bright bands of this comet occupy.

This comet differs remarkably from the two small comets which I examined in the much smaller relative proportion of the light which forms a continuous spectrum. In Brorsen's comet, as it now appears, the bright middle part of the nebulosity seems to have a constitution analogous at least to that of the nucleus, and to be self-luminous; in the other comets the coma, which surrounded a distinctly marked nucleus, gave a continuous spectrum. The three comets resemble each other in the circumstance that the light of the bright central part was emitted by the cometary matter, while the surrounding nebulosity reflected solar light.

The telescopic observations of the heads of Donati's comet and of other large comets have shown that the luminous material is not at once driven off into the outer portions of the coma and the tail, but usually forms in front of the nucleus a dense luminous cloud, which for a time seems to be identical in the character of its light with that of the nucleus. It is, I believe, the outer portions only of the coma, which are frequently separated by dark spaces from the nucleus, and the tail, which the polariscope has shown to shine by reflected light.

The positions of the bands in this comet would seem to indicate a chemical

* *Astronom. Nachrichten*, No. 1488.

† *Phil. Trans.*, 1864, p. 158.

constitution different from that of the nebulæ, which give a spectrum of bright lines. It will be seen in the diagram that, though the brightest of the bands in the spectrum of the comet differs but little in position from the brightest line of the nebulæ, the other bands are found in parts of the spectrum widely removed from those in which the other lines of the nebulæ occur. The suggestion presents itself whether the broad nebulous bands may not indicate conditions of temperature and molecular state different from those which occur in the gaseous nebulæ. Plücker has shown that nitrogen and some other substances give totally different spectra, under different conditions of temperature and tension. The spectrum of this comet, however, does not resemble the other spectrum of nitrogen, which Plücker distinguishes as the spectrum of the first order.*

OBSERVATIONS OF COMET II, 1868

(From *Phil. Trans.*, vol. clviii., p. 529)

ON June 13 a comet was discovered by Dr. Winnecke, and also independently the same night by M. Becquet, Assistant Astronomer at the Observatory of Marseilles.

I was prevented by buildings existing near my observatory from making observations of this comet before June 22. On that evening the comet was much brighter than Brorsen's comet, a description of the spectrum of which I recently presented to the Royal Society,† and it gave a spectrum sufficiently distinct for measurement and comparison with the spectra of terrestrial substances.

Telescopic Appearance of the Comet.—A representation of the comet as it appeared on June 22 at 11 p.m. is given in fig. 34, on page 283. The comet consisted of a nearly circular coma, which became rather suddenly brighter towards the centre, where there was a nearly round spot of light. The diameter of the coma, including the exterior faint nebulosity, was about 6' 20". The tail, which was traced for more than a degree, was sharply defined on the following edge, but faded so gradually away on the opposite side that no limit could be perceived. No connection was traced between the tail and the brighter central part of the coma. The circular part of the coma was uninterrupted on the side of the tail, which appeared as an extension of the faint nebulosity which formed the extreme margin of the coma.

The bright roundish spot of light in the centre, when examined with eyepieces magnifying from 200 to 600 diameters, presented merely a nebulous light without a defined form.

* *Phil. Trans.*, 1865, p. 9.

† *Proc. Roy. Soc.*, vol. xvi., p. 386.

Spectrum of the Comet.—When a spectroscope furnished with two prisms of 60° was applied to the telescope, the light of the comet was resolved into three very broad bright bands, which are represented in the diagram.

In the two more refrangible of these bands the light was brightest at the less refrangible end, and gradually diminished towards the other limit of the bands. This gradation of light was not uniform in the middle and brightest band, which continued of nearly equal brilliancy for about one-third of its breadth from the less refrangible end. This band appeared to be commenced at its brightest side by a bright line.

The least refrangible of the three bands did not exhibit a similar marked gradation of brightness. This band, though of nearly uniform brilliancy throughout, was perhaps brightest about the middle of its breadth.

These characters, which are peculiar to the light emitted by the cometary matter, must be distinguished from some appearances which the bands assumed in consequence of the mode of distribution of the light in the coma of the comet. The two more refrangible bands became narrower towards their most refrangible side, as well as diminished in brightness. This appearance was obviously not due to any dissimilarity of the light in the parts of the coma, but to the circumstance that as the light of the coma became brighter towards the centre, it was emitted by a smaller area of the cometary matter. The strong light of the central spot could be traced the whole breadth of the band; but the light surrounding this spot, in proportion as it became fainter and broader, was seen for a shorter distance, so that the light from the faintest parts near the margin of the coma was visible only at the brightest side of the band. Since in the least refrangible band a similar gradation of light did not take place, this band appeared of nearly the same width throughout.

The increasing brightness of the coma up to the brilliant spot in the centre showed itself in this band as a bright axial line fading off gradually in both directions.

On this evening I took repeated measures of the positions of these bands with the micrometer attached to the spectroscope. These measures give the following numbers for the commencement and termination of the three bands on the scale adopted in the diagram:—

First band {
1094
1196

Second band {
1298
1440

Third band {
1589
1700

I could not resolve the bands into lines. When the slit was made narrow the bands became smaller both in breadth and length, from the invisibility of the fainter portions. I suspected, however, the presence of two or three bright lines in the bright central part of the middle band near its less refrangible limit. This part would consist chiefly of light from the bright central spot.

As has been stated, the middle band commences probably with a bright line; for the limit of the band is here abrupt and distinct. On the contrary, the exact point of commencement and termination of the other bands could not be observed with certainty.

I could perceive no other bands, nor light of any kind beyond the three bands, in the parts of the spectrum towards the red and the violet.

When the marginal portions of the coma were brought upon the slit, the three bands of light could still be traced. When, however, the spectrum became very faint, it appeared to me to become continuous; but the light was then so very feeble that it could not be traced beyond the three bands towards the violet or the red.

On this evening I observed the spectrum of the comet in a larger spectroscope, which gives a dispersion equal to about five prisms. In this instrument the middle band was well seen. It retained its nebulous, unresolved character, and the abrupt commencement, as if by a bright line, already mentioned, was distinctly seen.

For convenience of comparison, the spectrum of Brorsen's comet, and that of the gaseous nebulæ, have been added to the diagram, fig. 35, page 283. The spectrum of Brorsen's comet consisted of three bright bands and a faint continuous spectrum. These bands appeared, as represented in the diagram, narrower than those of the comet now under examination. It is not possible to say to what extent this circumstance may be due to the much feebler light of this comet. Though the bands of Brorsen's comet fall within the limits of position occupied by the broad bands of Comet II, they do not correspond to the brightest parts of these bands. In the middle band I suspected two bright lines, which appeared shorter than the band, and may be due to the nucleus. Brorsen's comet differed from the two small comets which I had previously examined* in the much smaller relative proportion of the light which forms a continuous spectrum. In Brorsen's comet the bright middle part of the coma seemed to emit light similar to that of the nucleus, in the other comets the coma appeared to give a continuous spectrum. The three comets resembled each other in the circumstance that the light of the central part was emitted by the cometary matter, while the surrounding nebulosity reflected solar light.

It will be seen in the diagram that the bands of Brorsen's comet, and those of Comet II, occupy positions in the spectrum widely removed from those in which the lines of the nebulæ occur. The spectra of the gaseous nebulæ consist of true lines, which become narrow as the slit is made narrower.

The following day I carefully considered these observations of the comet

* Comet I, 1866, *Proceedings*, vol. xv., p. 5, and Comet 1867, *Monthly Notices R.A.S.*, vol. xxvii., p. 288.

with the hope of a possible identification of its spectrum with that of some terrestrial substance. The spectrum of the comet appeared to me to resemble some of the forms of the spectrum of carbon which I had observed and carefully measured in 1864. On comparing the spectrum of the comet with the diagrams of these spectra of carbon, I was much interested to perceive that the positions of the bands in the spectrum, as well as their general characters and relative brightness, agreed exactly with the spectrum of carbon when the spark is taken in olefiant gas.

These observations on the spectrum of carbon were undertaken in continuation of my researches "On the Spectra of the Chemical Elements."* I have not presented them to the Royal Society, as they are not so complete as I hope to make them.

Though the essential features of the spectrum of carbon remained unchanged in all the experiments, certain modifications were observed when the spectrum was obtained under different conditions. One of these modifications, which was referred to in my paper "On the Spectra of the Chemical Elements,"† may be mentioned here. One of the strongest of the lines of carbon is a line in the red a little less refrangible than the hydrogen line, which corresponds to Fraunhofer's C. Now this line is not seen when the carbon is subjected to the induction-spark in the presence of hydrogen. Two of the other modifications of the spectrum of carbon are given in fig. 35, p. 283. The first spectrum represents the appearance of the spectrum of carbon when the induction-spark, with Leyden jars intercalated, was taken between the points of wires of platinum sealed in glass tubes, and placed almost in contact in olive-oil. In this spectrum are seen the principal strong lines which distinguish carbon. The shading of fine lines which accompanies the strong lines cannot be accurately represented, on account of the small size of the diagram. A spectrum essentially the same is produced when the spark is taken in a current of cyanogen. It may be mentioned that when the heating-power of the spark was reduced below a certain limit, though the decomposition of the oil still took place, the carbon was not volatilised, and the spectrum was continuous.

The third spectrum in the diagram represents the modification of this typical spectrum when the induction-spark is taken in a current of olefiant gas. The highly heated vapour of carbon emits light of the same refrangibilities as in the case of the oil; but the separate strong lines, with a similar power of spark, were no longer to be distinguished. The shading, when the carbon was obtained from the olefiant gas, was not composed of numerous fine lines, but appeared as an unresolved nebulous light.

Of course in all these experiments the lines of the other elements present were also seen, but they were known, and could therefore be disregarded.

* *Phil. Trans.*, 1864, p. 139.

† *Ibid.*, p. 145.

In the case of the spark in olefiant gas, the three bands in the diagram constitute the whole spectrum, with the exception of a faint band in the more refrangible part of the spectrum.

It was with the spectrum of carbon, as thus obtained, that the spectrum of the comet appeared to agree. It seemed, therefore, to be of much importance that the spectrum of the spark in olefiant gas should be compared directly in the spectroscope with the spectrum of the comet. The comparison of the gas with the comet was made the same evening, June 23.

My friend, Dr. William Allen Miller, visited the observatory on this evening, and kindly took part in the following observations.

The general arrangement of the apparatus with which the comparison was made is shown in the following diagram.

A glass bottle converted into a gas-holder, *a*, contained the olefiant gas. This was connected by means of a flexible tube with a glass tube *b*, into which were soldered two platinum wires. The part of the tube in front of the points of the wires had been cut away, and the surfaces carefully ground. A small plate of glass closed the opening by being held in its place by a band of vulcanised india-rubber. This tube was arranged in its proper position before the small mirror of the spectroscope *c*, by which the light of the spark was reflected into the instrument, and its spectrum was seen immediately beneath the spectrum of the comet. The spectroscope employed was furnished with two prisms of 60° .

The brightest end of the middle band of the cometic spectrum was seen to be coincident with the commencement of the corresponding band in the spectrum of the spark. As this limit of the band was well defined in both spectra, the coincidence could be satisfactorily observed up to the power of the spectroscope; and may be considered to be determined within about the

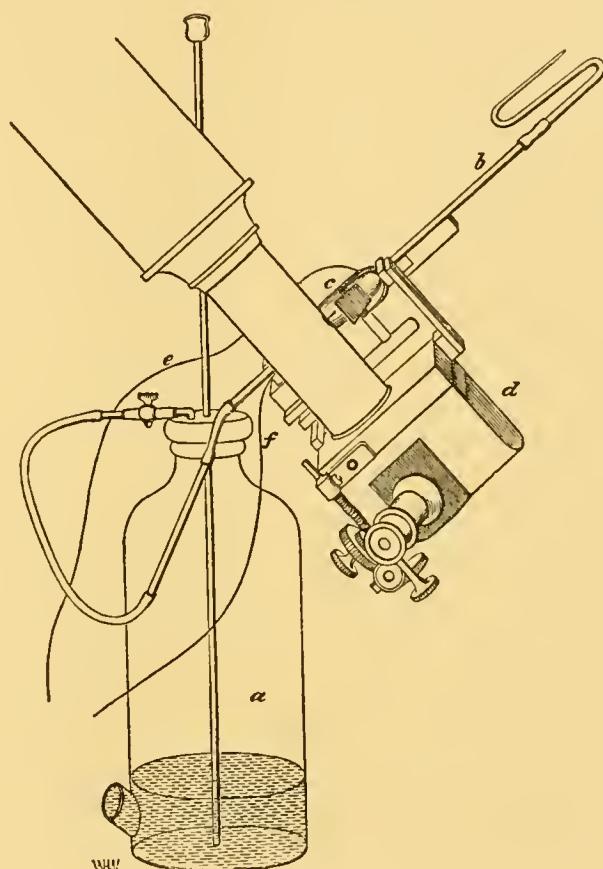


Fig. 33.

distance which separates the components of the double line D. As the limits of the other bands were less distinctly seen, the same amount of certainty of exact coincidence could not be obtained. We considered these bands to agree precisely in position with the bands corresponding to them in the spectrum of the spark.

The apparent identity of the spectrum of the comet with that of carbon rests not only on the coincidence of position in the spectrum of the bands, but also upon the very remarkable resemblance of the corresponding bands in their general characters and in their relative brightness. This is very noticeable in the middle band, where the gradation of brightness is not uniform. This band in both spectra remained of nearly equal brightness for the same proportion of its length.

On a subsequent evening, June 25, I repeated these comparisons, when the former observations were fully confirmed in every particular. On this evening I compared the brightest band with that of carbon in the larger spectroscope, which gives a dispersion of about five prisms.

The remarkably close resemblance of the spectrum of the comet to the spectrum of carbon necessarily suggests the identity of the substances by which in both cases the light was emitted.

It may be well to state that some phosphorescent and fluorescent bodies give discontinuous spectra in which the light is restricted to certain ranges of refrangibility. There are, however, several considerations which seem to oppose the idea that the light of comets can be of a phosphorescent character. Phosphorescent bodies are usually so highly reflective that the phosphorescence emitted by them is not seen so long as they are exposed to light. This comet was still in the full glare of the sun, and yet the continuous spectrum corresponding to reflected solar light was of extreme feebleness compared with the three bright bands which we have under consideration. The phenomenon of phosphorescence seems to be restricted to bodies in the solid state—a condition which is not apparently in accordance with certain phenomena which have been observed in large comets, such as the outflow of the matter of the nucleus, and the formation of successive envelopes.

There are, indeed, some phenomena of fluorescence, such as that of a nearly transparent liquid becoming an object of some brightness by means of the property which it possesses of absorbing the nearly invisible rays of the spectrum, and dispersing them in a degraded and much more luminous form, which are less obviously inconsistent with cometary phenomena than are those of phosphorescence.

The violent commotions and internal changes which we witness in comets when near the sun seem, however, to connect the great brightness which they then assume more closely with that part of the solar force we call heat. There

is also to be considered the fact of the polarised condition of the light of the tail and some parts of the comæ of comets, which shows that a part of their light is reflected.

The observations of the spectrum of Comet II contained in this paper, which show that its light was identical with that emitted by highly heated vapour of carbon, appear to be almost decisive of the nature of cometary light. The great fixity of carbon seems indeed to raise some difficulty in the way of accepting the apparently obvious inference of these prismatic observations. Some comets have approached the sun sufficiently near to acquire a temperature high enough to convert even carbon into vapour.* Indeed, for these comets a body of great fixity seems to be necessary. In the case of comets which have been submitted to a less fierce glare of solar heat, it may be suggested that this supposed difficulty is one of degree only; for we do not know of any conditions under which even a gas, permanent at the temperature of the earth, could maintain sufficient heat to emit light, a state of things which appears to exist permanently in the case of the gaseous nebulæ.

If the substance of the comet be taken to be pure carbon, it would appear probable that the nucleus had been condensed from the gaseous state in which it existed at some former period. It would therefore probably consist of carbon in a state of excessively minute division. In such a form it would be able to take in nearly the whole of the sun's energy, and thus acquire more speedily a temperature high enough for its conversion into vapour. In the liquid or gaseous state, or in a continuous solid state, this substance appears, from Dr. Tyndall's researches, to be diathermanous. Still, under the most favourable of known conditions, the solar heat to which the majority of comets are subjected would seem to be inadequate to the production of luminous vapour of carbon.

It should be stated that olefiant gas when burnt in air may give a similar spectrum of shaded bands. If the gas be ignited at the orifice of the tube from which it issues, the flame is brilliantly white, and gives a continuous spectrum. When a jet of air is directed through the flame it becomes less luminous, and of a greenish-blue colour. The spectrum is now no longer continuous, but exhibits the bands distinctive of carbon. Under these circumstances, for obvious reasons, the bright lines of the hydrogen spectrum are not seen. In this way a spectrum resembling that of the comet may be obtained, with the difference that the fourth more refrangible band, which was not seen in the cometic spectrum, is stronger relatively to the other bands than is the

* The comet of 1843 "approached the luminous surface of the sun within about a seventh part of the sun's radius. The heat to which the comet was subjected (a glare as that of 47,000 suns such as we experience the warmth of) surpassed that in the focus of Parker's great lens in the proportion of $24\frac{1}{2}$ to 1 without, or $3\frac{1}{2}$ to 1 with the concentrating lens. Yet that lens so used melted cornelian, agate, and rock-crystal."—Sir John Herschel, "Outlines of Astronomy," 7th edit., p. 401.

case when the spark is taken in olefiant gas. If we were to conceive the comet to partially consist of a compound of carbon and hydrogen, we should diminish in some degree the necessity for the excessively high temperature which pure carbon appears to require for its conversion into luminous vapour. If, indeed, it were allowable to suppose a state of combustion, with oxygen or some other element, set up by the solar heat, we should have an explanation of a possible source of a degree of heat sufficient to render the cometary matter luminous, and which the sun's heat would be directly inadequate to produce.

There is one observation made by Bunsen which appears to stand as an exception to the rule that only bodies in the gaseous state give, when luminous, discontinuous spectra. Bunsen discovered that solid erbia, when heated to incandescence, gives a spectrum containing bright bands. It is therefore conceivable, though all the evidence we possess from experience is opposed to the supposition, that carbon might exist in some form in which it would possess a similar power of giving a discontinuous spectrum without volatilisation. There is the further objection to this hypothesis, that the telescopic phenomena observed in comets appear to show that vaporisation does usually take place.

However this may be, a state of gas appears to accord with the very small power of reflection which the matter of the coma of this comet possessed, as was shown by the great faintness of this continuous spectrum.

A remarkable circumstance connected with comets is the great transparency of the bright cometary matter. The most remarkable instance is that of Miss Mitchell's comet in 1847, which passed centrally over a star of the fifth magnitude. "The star's light appeared in no way enfeebled, yet such a star would be completely obliterated by a moderate fog extending a few yards from the surface of the earth."* We do not know what amount of transparency is possessed by the vapour of carbon, but the absence of a continuous spectrum seems to show that, as it existed in the comet, it was almost perfectly transparent. The light of a star would suffer, therefore, only that kind and degree of absorption which corresponds with its power of radiation, as shown by its spectrum of bright lines. As these occur in the brightest part of the spectrum, we should expect a noticeable diminution of the star's light, if it were not for the luminous condition of the gas, in consequence of which it would give back to the beam light of precisely the same refrangibilities as it had taken, and so enable the part of the field occupied by the image of the star to appear of its original brightness, or nearly so. This state of things would not prevent an apparent diminution of the star's light from the effect upon the eye of the brightness of the surrounding field. In the case of the tails of comets, the great transparency observed is more probably to be referred to the widely scattered condition of the minute particles of the cometary matter.

* "Outlines of Astronomy," p. 373.

I may be permitted to repeat here a passage from my paper on the Spectrum of Comet I, 1866.*

"Terrestrial phenomena would suggest that the parts of a comet which are bright by reflecting the sun's light are probably in the condition of fog or cloud.

"We know, from observation, that the comæ and tails of comets are formed from the matter contained in the nucleus.†

"The usual order of the phenomena which attend the formation of a tail appears to be that, as the comet approaches the sun, material is thrown off, at intervals, from the nucleus in the direction towards the sun. This material is not at once driven into the tail, but usually forms in front of the nucleus a dense luminous cloud, into which for a time the bright matter of the nucleus continues to stream. In this way a succession of envelopes may be formed, the material of which afterwards is dissipated in a direction opposite to the sun, and forms the tail. Between these envelopes dark spaces are usually seen.

"If the matter of the nucleus is capable of forming by condensation a cloud-like mass, there must be an intermediate state in which the matter ceases to be self-luminous, but yet retains its gaseous state, and reflects but little light. Such a non-luminous and transparent condition of the cometary matter may possibly be represented by some at least of the dark spaces which, in some comets, separate the cloud-like envelopes from the nucleus and from each other."

Now considerable differences of colour have been remarked in the different parts of some comets. The spectrum of this comet would show that its colour was bluish green. Sir W. Herschel described the head of the comet of 1811 to be of a greenish or bluish-green colour, while the central point appeared to be of a pale ruddy tint. The representations of Halley's comet at its appearance in 1835, by the elder Struve, are coloured bluish green, and the nucleus on October 9 is coloured reddish yellow. He describes the nucleus on that day thus : "Der Kern zeigte sich wie eine kleine, etwas ins gelbliche spielende, glühende Kohle von langlicher Form."‡ Dr. Winnecke describes similar colours in the bright comet of 1862. "Die Farbe des Strahls erscheint mir gelbröthlich ;

* *Proc. Roy. Soc.*, vol. xv., p. 5.

† The head of Halley's comet in 1835 in a telescope of great power "exhibited the appearance of jets as it were of flame, or rather of luminous smoke, like a gas fan-light. These varied from day to day, as if wavering backwards and forwards, as if they were thrown out of particular parts of the internal nucleus or kernel which shifted round, or to or fro by their recoil like a squib not held fast. The bright smoke of these jets, however, never seemed to be able to get far out towards the sun, but always to be driven back and forced into the tail as if by the action of a violent wind setting against them (always *from* the sun), so as to make it clear that the tail is neither more nor less than the accumulation of this sort of luminous vapour darted off, in the *first instance towards the sun*, as it were something raised up, and, as it were, exploded by the sun's heat out of the kernel, and then immediately and forcibly turned back and *repelled from the sun*."—Sir John Herschel, "Familiar Lectures on Scientific Subjects," p. 115.

‡ "Beobachtungen des Halleyschen Cometen," S. 41.

die des umgebenden Nebels (vielleicht aus Contrast) mattbläulich. . . . Die Farbe der Ausströmung erscheint mir gelblich; die Coma hat bläuliches Licht."*

Now carbon, if incandescent in the solid state, or reflecting, when in a condition of minute division, the light of the sun, would afford a light which, in comparison with that emitted by the luminous vapour of carbon, would appear as yellowish or approaching to red.

The views of comets presented in this paper do not, however, afford any clue to the great mystery which surrounds the enormous rapidity with which the tail is often projected to immense distances.† There are not any known properties peculiar to carbon, even when in a condition of extremely minute division, which would help to a solution of the enigma of the violent repulsive power from the sun which appears to be exerted upon cometary matter shortly after its expulsion from the nucleus, and upon matter in this condition only. It may be that this apparent repulsion takes place at the time of the condensation of the gaseous matter of the coma, into the excessively minute solid particles of which the tail probably consists. There is a phenomenon occasionally seen which must not be passed without notice—namely, the formation of faint narrow rays of light, or secondary tails, which start off usually from the brightest side of the principal tail, not far from the head. Sir John Herschel‡ considers that "they clearly indicate an analysis of the cometic matter by the sun's repulsive action, the matter of the secondary tails being darted off with incomparably greater velocity (indicating an incomparably greater intensity of repulsive energy) than that which went to form the primary one." The important differences which exist between the spectrum of Brorsen's comet and that of Comet II, 1868, appear to show that comets may vary in their constitution. If the phenomenon of the secondary tails were observed in a comet which, like Comet II, 1868, appears to consist of carbon, the analytical action supposed by Sir John Herschel might be to separate between particles of carbon in different conditions, or possibly in a state of more or less subdivision. The enormous extent of space, sometimes a hundred millions of miles in length, over which a comparatively minute portion of cometary matter is in this way diffused, would suggest that we have in this phenomenon a remarkable instance of the extreme division of matter. Perhaps it would be too bold a speculation to suggest that, under the circumstances which attend the condensation of the gaseous matter into discrete solid particles, the division may be pushed to its utmost limit, or nearly so. If we could conceive the separate atoms to be removed beyond the sphere of their mutual attraction of cohesion, it might be that they

* "Mémoires de l'Académie Impériale des Sciences de St. Pétersbourg," tome vii., No. 7.

† Euler's view that the waves of light exert a pressure on the body upon which they fall had not then been proved theoretically by Maxwell to be true. It was not until the beginning of the present century that the pressure of radiation was shown by experiment to actually exist. (1909.)

‡ "Familiar Lectures on Scientific Subjects," p. 129.

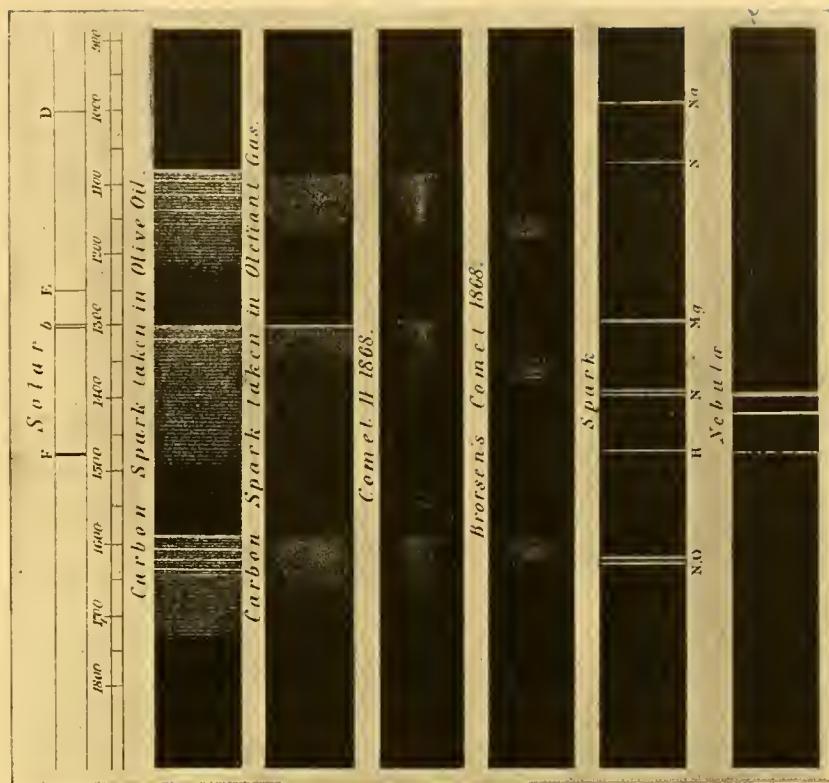


Fig. 35.



Fig. 34.

would be affected by the sun's energy in a way altogether different from that of which we have been hitherto the witnesses upon the earth.

Though comets may differ in their constitution, reference may be permitted to the periodical meteors which have been shown to move in orbits identical with those of some comets. If these consist of carbon, we might have some explanation of the appearances presented by these meteors, though their light is doubtless greatly modified by that of the air rendered luminous by their passage, as well as by the degree of temperature to which they are raised. Carbon is abundantly present in some meteorites, but we have no certain evidence at present that the periodical meteors belong to this class of celestial bodies.*

ON THE SPECTRUM OF COMET I, 1871

(From *Proc. Roy. Soc.*, vol. xix., p. 490)

ON April 7 a faint comet was discovered by Dr. Winnecke. I observed the comet on April 13 and May 2. On both days the comet was exceedingly faint, and on May 2 it was rendered more difficult to observe by the light of the moon and a faint haze in the atmosphere. It presented the appearance of a small faint coma, with an extension in the direction from the sun.

When observed in the spectroscope, I could detect the light of the coma to consist almost entirely of three bright bands.

Measures of the bands showed that this comet is similar in constitution to the comets which I examined in 1868.

NOTE ON THE SPECTRUM OF ENCKE'S COMET

(From *Proc. Roy. Soc.*, vol. xx., p. 45, 1871)

I GIVE the following observations of Encke's comet, and of the spectrum of its light, in the order of the dates of the evenings on which they were made.

October 17.—The comet presented the appearance of a nearly circular faint nebulosity, in which no condensation could be certainly distinguished.

November 7.—By this time an important change had taken place in the appearance of the comet. There was now a strong condensation of light towards the east. The more condensed part of the comet, which was fan-shaped, was bounded on the eastern side by a tolerably defined contour, which approached in form to a parabolic curve. Surrounding this brighter portion of

* In fig. 35, the bright line at the beginning of the middle band of the spectrum of olefiant gas is made too strong.

the comet was a much fainter nebulosity, of which the boundary on the eastern side appeared to form a line at right angles to the axis of the comet.

I suspected a very minute stellar nucleus just within the eastern extremity of the brighter condensed part, and to a small extent north of the comet's axis.

November 8.—The description given yesterday is applicable to the comet to-night. The brighter part appears more defined and in stronger contrast to the fainter outlying nebulosity. The nucleus is now visible with certainty. On the western preceding side of the comet, the side towards the sun, the cometary light becomes gradually fainter and more extended until it is lost to view.

On this evening the light of the comet was examined by the spectroscope. The larger part of the light was resolved by the prism into a bright band in the green part of the spectrum. The band was defined at its less refrangible limit, and gradually faded towards the blue. The micrometer gave 5160 millionths of a millimetre as the wave-length of the less refrangible boundary of the band. Two other bright bands were occasionally suspected; one of them

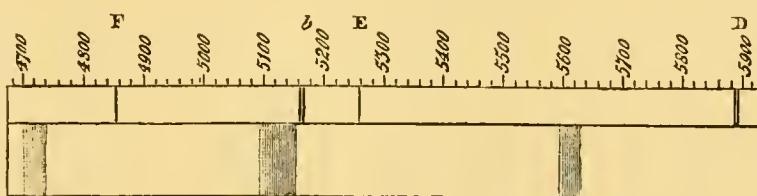


Fig. 36.

appeared to be about two-thirds of the distance from the bright band towards D, the other a little distance beyond F. No continuous spectrum could be detected. The nucleus was probably much too minute and faint to give a continuous spectrum that could be seen.

No difference in the spectrum was seen when the slit was moved over the comet in different directions, as far as its feeble light permitted.

The spectrum of a hydrocarbon, giving the bands which appear to be due to carbon, was then reflected into the instrument, and observed simultaneously with that of the comet. The band in the green was found to be identical in position with the brightest of the bands of carbon, and to be similar in gradation of brightness from its less refrangible limit.

November 9.—The observations of yesterday were confirmed. The second more refrangible band, which was then caught only by glimpses, was found to be coincident with the third band in the carbon spectrum. The wavelength of the less refrangible limit was about $\lambda 4735$. The least refrangible of the three cometary bands could be seen only occasionally.

November 12.—The observations on this evening contain no new facts.

November 13.—To-night the nucleus appears as a minute, well-defined stellar point.

In the spectroscope the three bands are distinctly seen. The position in the spectrum of the least refrangible band corresponds with the first band of the carbon spectrum; it commences from the red, with a wave-length of about $\lambda 5632$.

Attempts were made with a double-image prism, a Nicol's prism, and a Nicol's prism combined with a Savart's plate to detect polarised light in the comet, but without success.

November 14.—The form of the comet remains nearly the same. The outlying nebulosity is now chiefly on the south of the axis of the comet. The nucleus appears to be precisely at the extreme eastern limit of the brighter, more condensed part of the comet.

The same spectrum was seen, but fog coming on interrupted the observations.

On this evening an attempt was made again to detect polarised light. A double-image prism was placed between the eyepiece and the eye. The prism was brought into four different positions 90° apart. At each position of the prism an attempt was made to estimate the relative brightness of the two images. The power of the prism was just sufficient to give two images of the comet without their overlapping. The difference in brightness of the images was exceedingly small; I could not be certain that any appreciable difference really existed. However, I attempted in each case to select one of the two images as the brighter one. Afterwards I determined the position of the prism at the four different estimations, and I then found that three of the estimations were in accordance with a portion of the comet's light being polarised in a plane passing through the sun, and one in opposition to that supposition. I hesitate to attach any positive value to these observations; but they may perhaps be taken as showing that no considerable part of the comet's light is polarised.

The foregoing observations appear to show that the spectrum of this comet is identical with that of Comet II, 1868, a description of which I had the honour to present to the Royal Society.*

It is worthy of notice that the cometary matter appears drawn out and diffused towards the sun, and that it has not yet come under the influence of the force, or been subjected to the conditions, whatever they may be, by which in most cases cometary matter appears to be powerfully repelled from the sun.

The observations were made with the telescope belonging to the Royal Society, of 15 inches aperture. The spectroscope contained one prism with a refracting angle of 60° , and the small observing telescope magnified six times.

* *Phil. Trans.*, 1868, p. 555, and plate xxxiii.

ON THE TELESCOPIC APPEARANCE OF ENCKE'S COMET

(From *Proc. Roy. Soc.*, vol. xx., p. 87, 1871)

THE first three figures which accompany this note represent the comet on evenings on which its appearance was described in a note on the spectrum of the comet which I had the honour to present to the Royal Society.* A continuance of bad weather prevented me from making later observations of the comet, with the exception of one evening, December 5, when fig. 1, Fig. 37, was obtained under unfavourable circumstances.

Fig. 1. November 7, 7.30 p.m. — From October 17, when the comet consisted of a nearly round nebulosity without condensation in any part, to November 7 no observations could be obtained. At the latter date the remarkable fan-form which distinguishes this appearance of the comet was already distinctly presented. The faint light by which the comet was surrounded terminated on the side from the sun, that from which the tail is usually projected, in a straight



Fig. 37.

* See preceding paper.

boundary at right angles to the longer axis of the comet. At the opposite side, that towards the sun, the faint nebulosity expanded and became fainter until it could be no longer traced. The minute stellar nucleus which was suspected at the eastern extremity of the fan is not marked in the figure.

Fig. 2. November 8, 7 p.m.—The fan was now brighter and more defined in form. The nucleus, as a minute bright point, appeared to be situated not at the extreme western point, but a little within it, towards the north.

The sides of the fan were slightly curved, suggesting an approach to a parabolic form.

The fan was brighter on the southern side. The eastern edge of the faint light by which the comet was surrounded still preserved a right line from north to south.

Fig. 3. November 14, 6.40 p.m.—The appearance of the comet was essentially the same as on November 8.

The bounding lines of the fan were perhaps less curved ; they enclosed an angle of from 85° to 90° .

The nucleus had become brighter, and now appeared to form the extreme eastern point of the fan.

No prolongation of the eastern boundary, where the tail is usually formed, was seen.

Fig. 4. December 5, 5.30 p.m.—Thin mist in the atmosphere allowed the brighter parts only of the comet to be satisfactorily observed.

The condensation of light was now much stronger at the eastern end, but a defined nucleus was not detected.

The fan form was less marked ; the brighter part of the comet more resembled a brush-like flame.

The atmospheric haze nearly concealed the faint light surrounding the comet, but, by glimpses, a tail was now seen to project towards the east ; it was traced to a distance of about twice the length of the bright brush.

The tail appeared to come from the northern side of the longer axis of the comet, and to consist of a faint ray with sides nearly parallel.

As I am at present without a suitable micrometer, I was not able to take measures of the comet.

ON THE SPECTRUM OF COGGIA'S COMET

(From *Proc. Roy. Soc.*, vol. xxiii., p. 154, 1874)

IN the years 1866, 1868, and 1871* I had the honour to communicate to the Royal Society some observations with the spectroscope of five small comets, including Encke's comet at its return in 1871.

* *Proc. Roy. Soc.*, vol. xvi., p. 386, vol. xix., p. 490, vol. xx., p. 45 ; and *Phil. Trans.*, 1868, p. 555-

These observations showed that a great part of the light of these comets was not reflected solar light, but light emitted by the matter of the comets. Further, the coincidence which was found to exist, in the case of three of the comets, between the three bright bands into which their light was resolved by the prism and the spectrum of some compounds of carbon appeared to indicate the presence of that element, in some form, in the cometary matter. The comet now visible, which was detected by M. Coggia, April 17, 1874, is the first bright comet to which the spectroscope has been applied. The following spectroscopic observations of this comet were made from July 1 to July 15.

When the slit of the spectroscope was placed across the nucleus and coma, there was seen in the instrument a broad spectrum, consisting of the three bright bands which were exhibited by Comet II, 1868,* crossed by a linear continuous spectrum from the light of the nucleus.

In the continuous spectrum of the nucleus I was not able to distinguish with certainty any dark lines of absorption, or any bright lines other than the three bright bands.

Besides these spectra, there was also present a faint broad continuous spectrum between and beyond the bright bands.

When the slit was moved on to different parts of the coma, the bright bands and the faint continuous spectrum were observed to vary in relative intensity.

When the slit was brought back past the nucleus on to the commencement of the tail, the gaseous spectrum became rapidly fainter, until, at a short distance from the nucleus, the continuous spectrum predominated so strongly that the middle band only, which is the brightest, could be detected on it.

We have presented to us, therefore, by the light of the comet three spectra :

1. The spectrum of bright bands.
2. The continuous spectrum of the nucleus.
3. The continuous spectrum which accompanies the gaseous spectrum in the coma, and which represents almost entirely the light of the tail.

THE SPECTRUM OF BRIGHT BANDS

The three bright bands were obviously similar in position and character to those which were observed in Comet II, 1868. In that comet the bands could not be resolved into lines; but in the spectrum of the comet now under observation, on some occasions, especially during the early part of July, the three bands were partially resolved into lines. The resolution of the bands

* *Phil. Trans.*, 1868, pl. xxxiii.

was seen most distinctly at the boundary of the coma, where the continuous spectrum was very faint.

The bands appeared to me to be brighter relatively to the continuous spectrum during the early part of the time that the comet was under observation.

On July 7 the bands were compared directly with the spectrum of the induction-spark taken in a current of olefiant gas. I suspected a small shift of all three bands towards the more refrangible end of the spectrum.

July 8.—I made some measures of the want of coincidence of the less refrangible edge of the middle and brightest band with the corresponding part of the band in the spectrum of the blue part of a small oil-flame. Afterwards I found that the collimating lens had shifted during the taking of the measures. I repeated the observations on July 13. On this day I estimated the shift of the brightest band to be about $\frac{1}{4}$ of the distance of δ^2 to δ^3 . The other bands appeared to be similarly displaced in relation to the bands of the terrestrial spectrum. The estimation of the amount of displacement was rendered more difficult by the circumstance that the cometary band was not so bright at the less refrangible limit as was the band in the spectrum of the oil-flame. With this exception, the relative brightness of the different parts of the bands agreed with the corresponding parts of the bands in the terrestrial spectrum.

On the supposition of the identity of the comet's bands with those of the spectrum of carbon, the shift which was observed would indicate a relative motion of approach of the comet and the earth of about 40 miles per second, a velocity nearly double that of their actual relative motion.

According to a table of the comet's motion, kindly furnished to me by Mr. Hind, F.R.S., the comet was approaching the earth on that day with a velocity of about 24 miles per second. The part of the earth's orbital motion in the direction of the comet may be disregarded, as it was less than a mile per second.

In the foregoing observations the slit was placed on the brightest part of the envelope, close in front of the nucleus. Was any part of the shift due to the motion of the matter within the comet? If the measures taken on July 8, when the lens was found to have shifted, could be regarded as trustworthy, they would indicate a slightly larger shift on that day.

In connection with the question whether the bright bands were furnished by a vapour containing carbon in some form, it is of importance to notice that the bright line near G which accompanies the three bands in the spectrum of carbon and its compounds appears to be absent in the spectrum of the comet. I took some pains to satisfy myself that this line was not to be detected in the comet's spectrum. If it had been present with the same relative brilliancy which it possesses in the terrestrial spectrum, I should have been able to see

it easily. The relative faintness or entire absence of this more refrangible band might find its explanation possibly in the low temperature of the cometary matter.

If the bands are to be considered as due to carbon, we have to inquire in what form the carbon exists in the matter of the comet. In my paper on Comet II, 1868, I pointed out that though some comets have been exposed to an intense degree of solar radiation, and though carbon might exist possibly in some condition more easily volatilised than those with which we are acquainted on the earth, "still, under the most favourable of known conditions, the solar heat to which the majority of comets are subjected would seem to be inadequate to the production of luminous vapour of carbon." I then stated that the necessity for a very high temperature would be diminished if we were to conceive of the existence in the comet of a compound of carbon and hydrogen which could furnish those bands without undergoing decomposition.

The remarkable connection of the orbits of comets with those of swarms of meteors, together with the presence of hydrocarbons in many meteorites, would seem to suggest the probability that, if carbon be present in comets, it exists in combination with hydrogen.

I stated, in the paper quoted above, that the spectrum of bright bands was also obtained from cyanogen. In the case of the hydrocarbons, the spectrum of bands was accompanied by the lines of hydrogen; and when cyanogen was employed, the known complex spectrum of nitrogen was present. A spectrum essentially the same, but less complete, was obtained, together with the known lines of oxygen, when carbonic acid and carbonic oxide were employed.

THE CONTINUOUS SPECTRUM OF THE NUCLEUS

I was not able to satisfy myself of the existence in the continuous spectrum of the nucleus of any dark lines, nor of any bright lines, other than the three bright bands which have been described.

I found that the presence of the bright bands increased the relative brightness of the middle part of the linear continuous spectrum, so as to give an apparently smaller relative amplitude to the red and violet parts of the spectrum. This was particularly noticed to be the case during the first week of July. When some breadth was given to the spectrum by means of a cylindrical lens, the bright bands were clearly distinguished in it, and then the relative brightness of different parts of the continuous spectrum was more nearly that of an ordinary incandescent body. The blue end of the continuous spectrum appeared to fail abruptly a little beyond G, and I was not able to trace the spectrum beyond this point. I took this circumstance at first to show the absence of the violet rays, and consequently a low temperature in the nucleus. Afterwards,

when the solar spectrum was reduced to about the brightness of that of the comet, I observed a similar apparent abrupt termination of light at the same part of the spectrum, which is therefore a phenomenon due to the eye of the observer. Although it is probable that the violet rays are absent, or at least not present with any great intensity in the light of the nucleus, this observation of the apparent failure of the spectrum a little beyond G cannot, by itself, be accepted as a trustworthy proof that such is really the case.*

When the nucleus was examined in the telescope, it appeared as a well-defined minute point of light of great brilliancy. I suspected at times a sort of intermittent flashing in the bright point. The nucleus suggested to me an object on fire, of which the substance was not uniform in composition, so that at intervals it burned with a more vivid light. On July 6 the diameter of the nucleus, when measured with a power of 800, was $1''\cdot8$. On July 13 the measure was nearly double—viz. $3''$; but at this time the point of light was less defined. On July 15 the nucleus appeared elongated towards the following side of the comet, at an angle of about 40° to the comet's axis.

The nucleus appeared of an orange colour. This may be due in part to the effect of contrast with the greenish light of the coma. Sir John Herschel described the head of the comet of 1811 to be of a greenish or bluish-green colour, while the central point appeared to be of a pale ruddy tint. The elder Struve's representations of Halley's comet, at its appearance in 1835, are coloured green, and the nucleus is coloured reddish yellow. He describes the nucleus of October 9 thus: "Der Kern zeigte sich wie eine kleine, etwas ins gelbliche spielende, glühende Kohle von länglicher Form." Dr. Winnecke describes similar colours in the bright comet of 1862: "Die Farbe des Strahls erscheint mir gelbröthlich; die des umgebenden Nebels (vielleicht aus Contrast) mattbläulich. . . . Die Farbe der Ausströmung erscheint mir gelblich; die Coma hat bläuliches Licht."

THE CONTINUOUS SPECTRUM WHICH ACCOMPANIES THE GASEOUS SPECTRUM

This spectrum was observed in every part of the coma; near its boundary, and in the dark space behind the nucleus, the continuous spectrum became so faint as to be detected with difficulty, at the same time that the bright bands were distinctly visible.

The greater brightness of some parts of the envelopes and of the coma appeared to be due for the most part to the presence of a larger quantity of the matter which gives a continuous spectrum. When the slit was placed on these brighter parts of the comet, the gaseous spectrum did not become

* See later observations, pp. 295 and 297.

brighter in the same degree, but there was an increase in the brightness of the continuous spectrum.

Behind the nucleus, the bright bands became fainter relatively to the accompanying continuous spectrum, until the brightest band only could be detected. The more distant parts of the tail give probably a continuous spectrum only.

In the coma there was seen occasionally a remarkable inequality in the brightness of the continuous spectrum between the bands. On some occasions the light between the first and second band was bright, while in the other parts of the spectrum the light was faint.

On several evenings I satisfied myself that polarised light was present in every part of the comet. I do not think that the proportion of polarised light exceeded $\frac{1}{5}$ of the total light. The polarisation, as exhibited by the partial extinction of one of the images formed by a double-image prism, appeared to be more marked in the tail. It must be remembered that such would appear to be the case to some extent even if the proportion were not really greater,



Fig. 38.

because the same proportional diminution in a faint object is more appreciated by the eye. Still, there was probably a relatively large proportion of polarised light in the tail.

The reflected solar light would account for a large part of the continuous spectrum. To what source are we to ascribe the remaining light which the prism resolves into a continuous spectrum? Is it due to reflection from discrete particles, too large relatively to the wave-lengths of the light for polarisation to take place? or is it due to incandescent solid particles? From the co-existence of the band-spectrum, we can scarcely think of distinct masses of gas dense enough to give a continuous spectrum.

The difficulty which presents itself in accounting for sufficient heat to maintain this matter and the nucleus in a state of incandescence has also to be encountered in respect of the gaseous matter which emits the light which is resolved into the bright bands.

The solar radiation to which the comet was subjected would be inadequate to account for this state of things directly. Is there chemical action set up within the comet by the sun's heat? Is the comet's light due to electricity in any form excited by the effect of the solar radiation upon the matter of the comet? Are we to look for the source of the light to the friction of the particles of the cometary matter which has been thrown into violent agitation by the comet's approach to the sun?

The comet was unfavourably situated for examination from my observatory, as it was seen on a background of sky illuminated by the lights of London; and as it approached the horizon it became partially concealed by the chimneys of some neighbouring houses. Nearly the whole of the time that the comet was visible was consumed in the observations with the spectroscope; and a few sketches only were made of the appearances presented by the head of the comet in the telescope.

The two sketches which accompany this note (Fig. 38) were made on July 13 and 14. On the latter evening the fainter parts of the coma, which are wanting in the sketch, were rendered invisible by the bright background of sky. Two of the phases presented by the intersection of the envelopes are shown in the sketches. The narrow black channel behind the nucleus passed on the right-hand side of the nucleus (as seen in the telescope), where it terminated in a small round extension, presenting something of the appearance of a black pin, with its head by the side of the nucleus.

ON THE PHOTOGRAPHIC SPECTRUM OF COMET *b*, 1881(From *Report Brit. Assoc.*, 1881, p. 520; also *Proc. Roy. Soc.*, xxxiii., p. 1, 1881)

IN the years 1866 and 1868 I applied the spectroscope to the light of comets, and in the latter year I showed that the three bright bands in the visible part of the spectrum agree with the similar bright bands which are seen when an induction spark is taken in olefiant gas.* The same bands are also seen in the flames of many compounds of carbon. I was inclined at that time to consider that these bands were due to the vapour of carbon. Subsequent investigations which have been made on the spectra of the compounds of carbon appear to make it probable that these bands are the spectrum of a compound of carbon with hydrogen. The observations (1868) showed the presence of carbon, probably in combination with hydrogen, in the cometary matter.

Since that time until the present year, no comet has appeared sufficiently bright to allow of the observations on its spectrum being extended to the ultra-violet region. The apparatus with which I had successfully photographed the spectra of stars was especially suited to this purpose.† It consists essentially of a spectroscope, furnished with a prism of Iceland spar and lenses of quartz, placed so that the slit shall be in the principal focus of a mirror 18 inches in diameter, equatorially mounted, and driven by an electrically controlled clock.

On the evening of June 24 (1881) I directed this instrument, armed with a very sensitive gelatine plate, to the head of Comet *b*, so that the nucleus should be upon one half of the slit. After an exposure of one hour, the open half of the slit was closed, the shutter withdrawn from the other half, and the instrument was then directed to Arcturus for fifteen minutes.

After development the plate presented a very distinct spectrum of the comet, together with that of the star, for comparison.

The spectrum of the comet consists of two spectra superposed upon each other: a continuous spectrum, which extends from about F to a little distance beyond H. In this continuous spectrum can be seen the Fraunhofer lines G, h, H, K, and many others. This spectrum is therefore due to reflected solar light.

The second spectrum consists of two sets of bright lines, and a suspicion of the presence of a third set. These lines are obviously to be referred to original light from the comet.

The strongest set consists of two bright lines in the commencement of the ultra-violet region. Measures made by the aid of the comparison star-spectrum give for these bright lines the wave-lengths 3883 and 3870. The less refrangible

* *Phil. Trans.*, 1861, p. 556.† *Ibid.*, 1880, p. 669.

line is much stronger, and a faint luminosity can be traced from it to a little beyond the second line 3870. There can be, therefore, no doubt that these lines represent the brightest end of the ultra-violet group, which appears under certain circumstances in the spectra of the compounds of carbon. Professors Liveing and Dewar have found for the strong line at the beginning of the group, the wave-lengths 3882·7, and for the second line 3870·5.

I am also able to see upon the continuous solar spectrum a distinct, though fainter, impression of a group of lines between G and h. There can be little doubt that this group is the one for the least refrangible limit of which the wave-length 4220 is given by Professors Liveing and Dewar.

An increase of brightness in the continuous spectrum is also seen between h and H, which may be due to other bright lines, but the photograph is not strong enough to admit of any certain conclusion on this point.

On June 25 a second photograph was obtained with an exposure of an

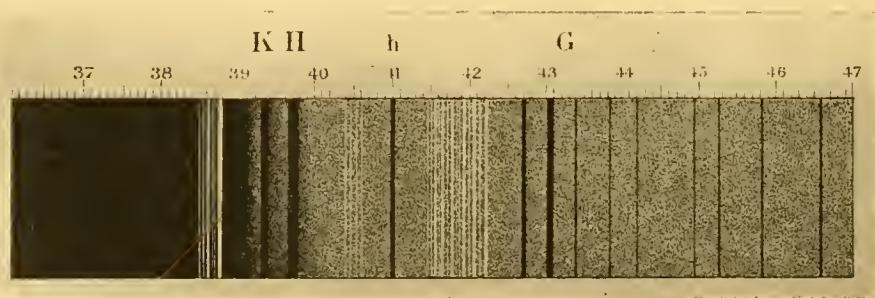


Fig. 39.

hour and a half. This photograph, notwithstanding the longer exposure, is fainter, but shows distinctly the bright lines in the ultra-violet, and the continuous spectrum.

These photographs confirm the results of my earlier observations on comets—that part of their light is reflected sunlight, and part is original light; and, further, that carbon is present in the cometary matter. The new bright groups in the comet's spectrum which the photographs have revealed to us are certainly characteristic of substances containing carbon.

In their paper "On the Spectra of the Compounds of Carbon,"* Professors Liveing and Dewar bring forward evidence to show that these two groups indicate the presence of cyanogen, and are not to be seen in hydrocarbons unless nitrogen is also present. If this be the case the photograph supplies us with strong evidence of the presence of nitrogen in the comet, in addition to the carbon and hydrogen shown to be there by the bright groups in the visible region of the spectrum. It is of great interest in connection with this

* *Proc. Roy. Soc., vol. xx., p. 494.*

result, now that Schiaparelli has shown us the close relationship of meteors and comets, to mention the results of Professor Graham's experiments on the occluded gases from the meteoric iron of Lenarto.* This iron gave nearly three times its volume of gas, consisting chiefly of hydrogen, with small quantities of carbonic oxide and nitrogen.

Professor Wright's examination of the stony meteorites shows the oxides of carbon, chiefly the dioxide, to be present in largest quantity; but he obtained also a small percentage of hydrogen and nitrogen.† Other kinds of meteors are known which contain hydrocarbons, even in considerable quantity. It is scarcely necessary to add that, under suitable conditions, the spectra of the gases from some meteorites will be similar to that observed from the light of comets.

Messrs. Liveing and Dewar's experiments would seem to show that a high temperature must be present in the comet, if the cyanogen is formed there, but if cyanides should be found in meteorites this necessity would not exist.

Whatever the views that may be entertained as to the forms of combination in which the carbon exists, there can be no doubt whatever of the presence of carbon in comets. I should mention that Mr. Lockyer regards the two bright groups seen in the photograph, and the three groups in the visible spectrum, to be due to the vapour of carbon at different heat-levels.‡

It is of importance to mention the strong intensity in the photograph of the lines 3883 and 3870 as compared with the continuous spectrum, and the faint bright group beginning at 4220. At this part of the spectrum, therefore, the light emitted by the cometary matter exceeded by many times the reflected solar light.

On August 21 I attempted to obtain, with an exposure of one hour, a photograph of the spectrum of a large comet which has appeared since Comet *c*, 1881. The evening was not very favourable, and the comet was at a low altitude and not so brilliant as Comet *b*. I am not able to see on the plate more than a faint trace of the brightest lines (W. L. 3883 and 3870) of the spectrum obtained from the former comet.

"ON THE PHOTOGRAPHIC SPECTRUM OF COMET I (WELLS), 1882"

(From *Proc. Roy. Soc.*, vol. xxxiv., p. 148, 1882)

ON the evening of Wednesday, May 31, I obtained a photograph of the spectrum of this comet with an exposure of an hour and a quarter. A spectrum

* *Proc. Roy. Soc.*, vol. xv., p. 502, 1867.

† *Amer. Journ. Science*, vol. x., July 1875.

‡ *Proc. Roy. Soc.*, vol. xxx., p. 461.

of α Ursæ Majoris was taken through the other half of the slit, on the plate, for comparison.

The photograph shows a strong continuous spectrum extending from about F to a little beyond H. In this continuous spectrum I am not able to distinguish the Fraunhofer lines. In this comet, therefore, at this time, the original light giving a continuous spectrum must have been much stronger relatively to the sunlight reflected than was the case in the comet of last year. It should be stated that the greater faintness of the present comet made it necessary to use a more open slit, which would cause the Fraunhofer lines to be less distinct; but the lines G, H, and K are to be clearly seen in the star's spectrum taken under the same conditions.

Eye observations by several observers on the visible spectrum of the comet had already shown that this comet, for the first time since spectrum analysis was applied to the light of these bodies in 1864, gives a spectrum which differs essentially from the hydrocarbon type to which all the comets previously examined spectroscopically (about twenty) belong.

In the visible spectrum bright lines, presumably of the vapour of sodium, and some other bright lines and bright groups of lines, have been seen. The hydrocarbon bands in this part of the spectrum have been suspected to be present by some observers.

The photographic spectrum differs greatly from that of the comet of last year.* I am not able to see the cyanogen group in the ultra-violet beginning at wave-length 3883, nor are the other two groups between G and λ and between λ and H to be detected.

The continuous spectrum, which extends from below F to a little distance beyond H, contains at least five brighter spaces, which are doubtless groups of bright lines, though it is not possible in the photograph to resolve them into lines. These places of greater brightness can be traced beyond the border of the continuous spectrum on the side which corresponds to the coma of the comet on the side next the sun. The light from this part of the comet gave a very much fainter continuous spectrum, for on the photographic plate it appears to be almost wholly resolved by the prism into these bright groups. One or two fainter groups are suspected to be present, but they are too indistinct to admit of measurement.

The five stronger bright groups are too faint at the commencement and ending of each group to permit of more than a measurement of the estimated brightest part of each bright space.

The positions of these brightest parts are—

$$\lambda 4769, \quad \lambda 4634, \quad \lambda 4507, \quad \lambda 4412, \quad \lambda 4253.$$

* *Proc. Roy. Soc.*, vol. xxxiii., p. 1.

Professor A. Herschel and Dr. von Konkoly pointed out long ago that the spectra of periodic meteors belonging to different swarms differ from each other, and the meteorites which come down to us differ greatly in their chemical constitution. It is not surprising to find the matter of the nucleus of this comet to exhibit a chemical difference from that of other comets.

In the diagram, the width of the continuous spectrum corresponds to the diameter of the nucleus. The bright bands extend into the coma on the side next the sun.



Fig. 40.

Section VII

SUN AND CORONA

LIST OF PAPERS

- “On the Bright Granules of the Solar Surface.”
Monthly Notices R.A.S., vol. xxvi., p. 260, 1866. P. 306.
- “Further Observations on the Spectra of some of the Stars and Nebulæ, with an Attempt to Determine therefrom whether these Bodies are Moving towards or from the Earth; also Observations on the Spectra of the Sun and of Comet II.”
Phil. Trans., vol. clviii., p. 529, 1868. P. 311.
- “On a Possible Method of Viewing the Red Prominences without an Eclipse.”
Monthly Notices R.A.S., vol. xxviii., p. 88, 1868. P. 316.
- “On a Possible Method of Viewing the Red Flames without an Eclipse.”
Monthly Notices R.A.S., vol. xxix., p. 4, 1868. P. 317.
- “Note on Attempts to Render the Prominences Visible without the Use of the Spectroscope.”
Monthly Notices R.A.S., vol. xxx., p. 36. P. 317.
- “Note on a Method of Viewing the Solar Prominences without an Eclipse.”
Proc. Roy. Soc., vol. xvii., p. 302, 1869. P. 318.
- “Note on the Wide Slit Method of Viewing the Solar Prominences.”
Proc. Roy. Soc., vol. xxi., p. 127, 1873. P. 319.
- “On Photographing the Solar Corona without an Eclipse.”
Proc. Roy. Soc., vol. xxxiv., p. 409, 1882. P. 319.

"On the Solar Corona." (Lecture.)

Proc. Roy. Inst., vol. xi., Part II., p. 202.

"On Some Results of Photographing the Solar Corona without an Eclipse."

Report Brit. Assoc., 1883, p. 351. P. 324.

"On the Corona of the Sun. The Bakerian Lecture, 1885."

Proc. Roy. Soc., 1885, p. 108. P. 327.

"Duplicity of the Solar Line D₃."

Astronom. Nachrichten, No. 3302, p. 229, July 19, 1895. P. 353.

"A suggested Explanation of the Solar Corona."

Astrophys. Journ., vol. xii., p. 279, 1900. P. 353.

HISTORICAL STATEMENT

(From *The Nineteenth Century Review*, June 1897)

ABOUT this time (1867) I devoted some attention to spectroscopic observations of the sun, and especially to the modifications of the spectrum which take place under the influence of the solar spots.

The aerial ocean around and above us, in which finely divided matter is always more or less floating, becomes itself illuminated, and a source of light, when the sun shines upon it, and so conceals, like a luminous veil, any object less brilliant than itself in the heavens beyond. From this cause the stars are invisible at midday. This curtain of light above us, at all ordinary times shuts out from our view the magnificent spectacle of red flames flashing upon a coronal glory of bright beams and streamers, which suddenly bursts upon the sight, for a few minutes only, when at rare intervals the light-curtain is lifted by the screening of the sun's light by the moon, at a total eclipse.

As yet the spectrum of the red flames had not been seen. If, as seemed probable, it should be found to be that of a gas, consisting of bright lines only, it was conceivable that the spectroscope might enable us so to weaken by dispersion the air-glare, relatively to the bright lines which would remain undispersed, that the bright lines of the flames might become visible through the atmospheric glare.

The historic sequence of events is as follows. In November 1866 Mr. Lockyer asked the question: "May not the spectroscope afford us evidence of the existence of the red flames, which total eclipses have revealed to us in the sun's atmosphere, though they escape all other methods of observation at other times?"

In the Report of the Council of the Royal Astronomical Society, read in February 1868, occurs the following statement, furnished by me, in which the explanation is fully given of the principle on which I had been working to obtain the spectrum of the red flames without an eclipse:

"During the last two years Mr. Huggins has made numerous observations for the purpose of obtaining a view, if possible, of the red prominences seen

during an eclipse. The invisibility of these objects at ordinary times is supposed to arise from the illumination of our atmosphere. If these bodies are gaseous, their spectra would consist of bright lines. With a powerful spectroscope the light reflected from our atmosphere near the sun's limb edge would be greatly reduced in intensity by the dispersion of the prisms, while the bright lines of the prominences, if such be present, would remain but little diminished in brilliancy. This principle has been carried out by various forms of prismatic apparatus, and also by other contrivances, but hitherto without success."

At the total eclipse of the sun, August 18, 1868, several observers saw the light of the red flames to be resolved in their spectrosopes into bright lines, among which lines of hydrogen were recognised. The distinguished astronomer, Janssen, one of the observers in India, saw some of the bright lines again the next day, by means of the principle described above, when there was no eclipse.

On October 29, Mr. Lockyer sent a note to the Royal Society to say that on that day he had succeeded in observing three bright lines of a fine prominence.

About the time that the news of the discovery of the bright lines at the eclipse reached this country, in September, I was altogether incapacitated for work for some little time through the death of my beloved mother. We had been all in all to each other for many years. The first day I was sufficiently recovered to resume work, December 19, on looking at the sun's limb with the same spectroscope I had often used before, now that I knew exactly at what part of the spectrum to search for the lines, I saw them at the first moment of putting my eye to the instrument.

As yet, by all observers the lines only of the prominences had been seen, and therefore, to learn their forms, it was necessary to combine in one design the lengths of the lines as they varied, when the slit was made to pass over a prominence. In February of the following year it occurred to me that, by widening the opening of the slit, the form of a prominence, and not its lines only, might be directly observed. This method of using a wide slit has been since, universally employed.

ON THE BRIGHT GRANULES OF THE SOLAR SURFACE, WITH REMARKS ON THE NATURE OF THESE BODIES

(From *Monthly Notices R.A.S.*, vol. xxvi., p. 260, 1866)

I EMPLOY the word *granules* in preference to the other names* which have been proposed for the bright particles of the solar surface, because, as Mr. Dawes,

* Stone calls them *rice-grains*; Nasmyth, *willow-leaves*; Dawes, *granulations* and *minute fragments of porcelain*; Chacornac, *crystals*; Brodie, *shingle-beach*. Sir W. Herschel's *corrugations* and *bright nodules* may refer to the groups of granules, and possibly sometimes to single granules.

who suggested this term, well observes, "the appellation *granulations* or *granules* assumes nothing either as to exact form or precise character."

In this paper I confine my remarks to the bright granules as they appear on those parts of the sun which are free from the disturbing forces or currents which are active in the areas of the spots. Under the influence of the forces by which the spots are produced the bright granules assume different, and with respect to their appearance on the general surface of the sun, irregular and unusual forms. In these regions of disturbance the granules often appear to coalesce, sometimes to be drawn out into very elongated forms, and occasionally to be wholly dissipated within the umbra of a spot. On those parts of the sun, however, where the spots are absent these granules appear to preserve, within not very wide limits, considerable general definiteness of form, of size, and of mode of grouping. It is to these normal characters only of the bright granules that the observations of the present paper refer.

In a note I give references to the more important observations of others of these interesting bodies.*

Distribution.—With the exception, mentioned already, of the areas containing spots, the bright granules are to be seen over the whole surface of the sun. Occasionally, granules preserving their normal characters may be detected in the penumbræ and the umbræ of spots. On one occasion, May 4, 1866, I resolved a large facula near the edge of the sun's disk into an aggregation of similar particles. Without the border of the facula were two or three isolated granules of equal brightness with those composing the facula. These granules appeared as if they had become detached from the group forming the facula.

Form.—When the granules are observed with powers of about 100 diameters, no comparison which has been made appears to me so appropriate as that to "rice-grains," suggested by Mr. Stone. If, however, higher powers are employed, this apparent regularity of figure and of size of the granules disappears to a great extent. Many of them are then seen to be nearly round, and not of the elongated form of rice-grains. Besides the oval and nearly round granules, may be observed irregular-shaped masses of almost every form. An important character common to all these bodies, whatever their form, is the irregular broken outline by which they are bounded. If, however, these smaller irregularities of figure be disregarded, the granules may be described generally

* Dawes, *Monthly Notices*, vol. xxiv., p. 140 and p. 161; Nasmyth, *ibid.*, vol. xxiv., p. 66; Stone, *ibid.*, vol. xxiv., p. 124; Lockyer, *ibid.*, vol. xxv., p. 237; Brodie, *ibid.*, vol. xxv., p. 233; Fletcher, *ibid.*, vol. xxv., p. 231; Huggins, vol. xxiv., p. 141; De La Rue, *Memoirs R.A.S.*, vol. xxxiii.; Chacornac, *Reader*, Jan. 7, 1865. See also, for the interpretation of these bodies, Faye, *Comptes rendus*, tom. lx., p. 138 and p. 468; Brayley, Knight's *Companion to the Almanac*, 1864, 1865, 1866, and *Ast. Register*, vol. ii., p. 75; De La Rue, Stewart, and Loewy, *Researches on Solar Physics*, 1st Ser.; Sir. J. Herschel, *Monthly Notices*, vol. xxv., p. 152.

as possessing a more or less oval form. The granules appear to me not to be flat disks, but bodies of considerable thickness.

In the interpretation of these bodies it must not be forgotten that minute irregularities which appear almost insignificant in our telescopes would not be little to an observer on the sun. If the granules could be viewed from a short distance they would appear probably as wildly rugged in irregularity of outline as are the clouds of our sky.

Size.—On April 26, the sun's image was allowed to pass before the wires of the micrometer placed at a small distance apart. The interval separating the wires appeared to include sometimes two and sometimes three of the granules which were in contact with each other. I found the value of the interval between the wires to be $2''\cdot59$. The average size, therefore, of those bodies may be taken roughly at $1''$ in diameter, and the average longer diameter of the more oval particles at about $1''\cdot5$. This estimation agrees closely with the size assigned to them by Mr. Stone.

On some small areas of the solar surface the groups appeared to be composed of granules of nearly the same size, whilst on neighbouring areas a considerable difference in size existed between the adjacent granules. Occasionally a much larger granule was seen which might measure from $2''$ to $3''$ in diameter. Many of the granules were smaller than $1''$ in diameter.

Relative Position.—On many parts of the sun the granules, though they lie near together, are detached bodies separated from each other by small intervals. These groups of isolated granules are mingled with tesselated surfaces of bright matter formed of close aggregations of granules. The forms assumed by the groups of closely united granules are very various. Often they appear as nearly round or oval cloud-like masses, and when in this form have been probably mistaken by some observers for single granules. Sometimes these groups are long, irregularly formed bands, suggesting to an observer the rugged, broken sides of a range of mountains. On April 26, nearly in the centre of the sun's disk, I observed a long oval border of tesselated bright matter, enclosing an area over which the granules were sparsely distributed. Some of the more characteristic of the modes of grouping of the bright granules, which I have observed on different occasions, are given in a diagram which accompanies this paper.

It is in connection with these groups that the coarse mottling of the solar surface originates, for the difference in brightness of adjoining areas is produced mainly by the greater or less degree of closeness of aggregation of the bright granules. A second cause which contributes to the formation of the mottled appearance of the sun's disk is to be found in the different degrees of brightness of the material which fills the intervals between the groups of granules, and between single granules.

In addition to these phenomena, a careful observer will notice appearances which suggest considerable inequalities of *level* in the bright surface of the sun. The whole photosphere appears corrugated into irregular ridges and vales. Over this uneven surface, not unlike that of a stormy sea, the groups of granules which have been described are irregularly distributed.

Superposition?—I have not been able to satisfy myself whether the material of the photosphere immediately beneath the bright granules consists of an aggregation of separate particles. The appearances presented suggest that this matter is lower (nearer the sun's centre), and that generally the granules are

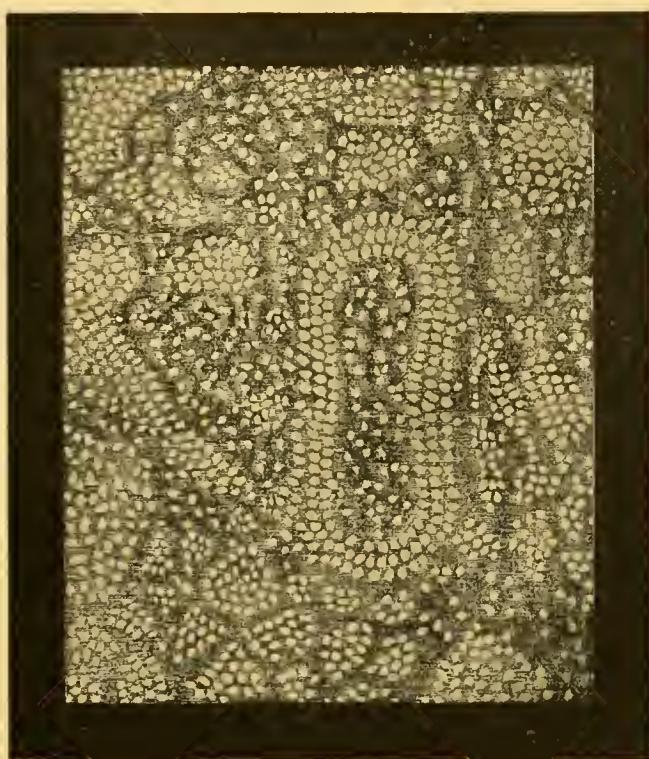


DIAGRAM OF THE DISTRIBUTION OF THE BRIGHT GRANULES ON
THE PARTS OF THE SUN WHICH ARE FREE FROM SPOTS.

Fig. 41.

bodies of considerable thickness, elevated above it, and surrounded by gaseous matter which is non-luminous in comparison with the extreme splendour of the granules. So superior in brightness are the granules, that the exterior layer, which is composed exclusively of them, must be regarded as the source of nearly the whole of the light, and probably also of the heat, which the sun emits. Except in the penumbra of a spot, under the influence of unusual currents, I incline to the opinion that the bright granules are not superposed on each other as long as they remain recognisable as such.

The phenomena would be well represented if we might suppose that the

granules are recently condensed incandescent clouds, that they slowly sink, merge into each other, become less and less luminous, and gradually dissipate into comparatively non-luminous gas. The dark pores would then be represented by the portions where complete vaporization had taken place.

Nature.—Mr. Dawes states that, after years of careful observation of these bright bodies, he considers them to be "merely different conditions of the surface of the comparatively large luminous clouds themselves—ridges, waves, hills, knolls, or whatever else they might be called—differing in form, brilliancy, and probably in elevation." I would venture to differ from this distinguished observer only so far as to suggest that the bright granules were originally *separate* clouds, though it may be that their under-surfaces soon begin to unite with the less luminous stratum of clouds beneath them.

I cannot express the ideas suggested to myself by observations of the sun more accurately than in the words of Sir John Herschel—"That it is hardly possible not to be impressed with the idea of a luminous medium intermixed but not confounded with a transparent and non-luminous atmosphere."

The extreme mobility and other phenomena of the bright matter suggest that it is present in the form of *cloud*.

The knowledge which the spectroscope affords of the chemical and physical constitution of solar matter, together with the phenomena of terrestrial flame, would suggest that in the greatly different powers of radiation possessed by matter in the solid, liquid, and gaseous state, combined with the processes of condensation and revaporation, a feasible explanation might be found of solar phenomena. However, the law of exchanges, for which we are greatly indebted to the original and important researches of Balfour Stewart, shows that in the case of the sun, if we suppose it to be, at the least, equally hot throughout its mass, the gas near the surface would not appear dark, as the umbra of a spot or a dark pore does, because its own feeble power of emission would be supplemented by its power in the inverse ratio of transmitting the radiation from the gas, or from the photosphere behind it.

At present, therefore, we do not appear to be able to explain satisfactorily the small brilliancy of the material between the bright particles and the darkness of the pores, which, like the umbra of a spot, appear to be at a lower elevation than the bright matter. It has been recently suggested that the dark umbra of a spot originates in a lower temperature produced by a down rush of cooler gas from above. It is of importance to know whether this hypothesis can be made to afford a probable explanation of the numerous dark pores and the small brilliancy of the material between the groups of bright granules.

If the granules are incandescent clouds, their general oval form may possibly be due to the influence of currents. We have to seek, besides the conditions

connected it may be with the high temperature of the sun, or with some peculiarity when in the gaseous state of the substances present in the photosphere in consequence of which there exists a general approximate uniformity of size, of form, and of mode of grouping of these incandescent bodies.

OBSERVATIONS OF THE SUN

(From *Phil. Trans.*, vol. clviii., p. 529, 1868)

I HAVE recently applied the large spectroscope described in this paper with some success to the examination of the spectrum of the umbra of a large sun-spot.

Before I describe the results of this examination, I will refer briefly to observations of the sun which I have made on many occasions, since 1864, with three distinct objects in view.

1. I have sought to discover if the spectrum of the light from near the sun's limb differs in any sensible degree from that of the light from the central parts of the disk. Since the diminished intensity of the marginal parts of the sun is probably due to the greater depth of solar atmosphere through which it had passed, it was conceivable that by its spectrum the light of these parts of the solar disk might exhibit some indications of the larger amount of absorbing medium which it had traversed.

Two different methods of observation were employed. The telescope, armed with one of the spectroscopes constructed for stellar observations, was directed to the sun. By the aid of the finder the telescope was moved so as to bring in succession upon the slit different parts of the solar disk. Though the detection of any difference depended upon the memory of the observer, still any considerable alteration would certainly have been noticed.

The other plan was to cause the sun's light, after reflection from a plane mirror attached to a heliostat moved by clockwork, to fall upon an achromatic object-glass of 6 feet focal length, by which an image of the sun was formed upon the slit of the large spectroscope which I employed for the examination of the spectra of the chemical elements.

By neither of these methods have I been able to detect any difference in the spectra of different parts of the sun's disk.

2. I have made numerous observations for the purpose of obtaining a view, if possible, of the red prominences which are seen during a solar eclipse. The invisibility of these objects at ordinary times is supposed to arise from the effect of the illumination of our atmosphere. If these bodies are gaseous, their spectra would consist of bright lines. With a powerful spectroscope the light from our atmosphere near the sun's limb would be greatly reduced in

intensity by the dispersion of the prisms, while the bright lines of the prominences, if such were present, would remain but little diminished in brilliancy. These observations have been made with different spectroscopes, and also with other contrivances arranged on the same principle, but hitherto without success.

[The observations made in India of the solar eclipse of August 18 have shown that the spectra of the prominences are discontinuous. Lieut. Herschel, R.E., who had charge of the instruments sent out by the Royal Society, determined approximately the position of three bright lines: one in the red about C, one apparently coincident with D, and one near F. On the day after the eclipse, M. Janssen, making use of a method similar to that described above, succeeded in observing the solar protuberances. On October 20, 1868, Mr. Lockyer also succeeded in viewing the spectrum of a protuberance. Now that the positions of the lines are known, one of the "other contrivances" mentioned above will probably succeed. It consisted of screens formed of absorptive media, by which light of all refrangibilities other than those corresponding to the lines of the flames might be absorbed. By this method the flames could be examined and measured.—October 30, 1868.]

3. The third object which I had proposed to myself was to seek to gain from an examination of the spectra of the umbræ and penumbræ of solar spots some information as to the nature of these remarkable phenomena.

I had already made some experiments in this direction when in August 1866 I received a note from M. Faye, in which he suggested to me the prismatic examination of solar spots, since, according to his theory of the constitution of the sun, the spectrum of the umbra of a spot should be compound, consisting of a continuous spectrum with dark lines, and a second spectrum of bright lines. My first observations were made with a direct-vision spectroscope of Hofmann, which was so arranged that the image of the sun was formed upon the slit, after the light had been enfeebled by reflection from a prismatic solar eyepiece.

When, by means of the finder, a spot was brought upon the slit, the feeble light from the umbra appeared as a narrow dark band upon the bright solar spectrum. The lines of Fraunhofer appeared stronger and thicker in the spectrum of the umbra.

In October 1866, Mr. Lockyer, who had independently made similar observations, presented a paper to the Royal Society,* in which he states that he observed the lines of absorption of the solar spectrum to appear thicker where they crossed the spectrum of the spot. He also states that he saw no indication of the presence of bright lines.

It was not until April 15, 1868, that a favourable opportunity occurred to examine a large spot with the new spectroscope described in this paper.

* *Proc. Roy. Soc.*, vol. xv., p. 256.

The presence of some haze in the atmosphere permitted the spectroscope to be applied directly to the telescope, and the slit to be placed at the focus of the object-glass. The slit was rotated so that its length was in the direction of the length of the spot, and when the middle of the umbra fell upon the slit, its spectrum appeared as a feebly illuminated band upon the bright solar spectrum. The band appeared divided into two parts by the spectrum of the bright prominence, which extended nearly across the umbra.

The phenomenon of an increase of thickness of the lines of Fraunhofer, which I had previously observed, was very marked.

It was obvious that a part only of the light which appeared to form the spectrum of the umbra came from that particular region of the sun. The imperfect transparency of our atmosphere causes it to become strongly illuminated when the sun shines upon the earth; and the brilliant light which is seen to be radiated by it near the sun's limb, is also radiated by that portion of the atmosphere which is between the observer and the sun. It might be, therefore, that the whole of the light which appeared to come from the umbra was really due to the illuminated intervening atmosphere. That such was not the case, and that some part of the light to which the spectrum was due came from the umbra, became evident when the telescope was moved so as to bring the sun's limb across the slit; for then the spectrum of the light from our atmosphere was less bright than the spectrum of the umbra of the spot.

In order to obtain some estimate as to how much of the apparent light from the umbra really came from it, I made use of a graduated wedge of neutral-tint glass. The spectrum of our atmosphere at the sun's limb became so dark that the lines could not be distinguished when the part of the wedge marked 10 was before the eye. To bring the spectrum of the umbra to about the same degree of invisibility the wedge had to be moved until the part marked 20 came before the eye. A photometric examination of the wedge shows that the light intercepted at 10 is to that intercepted at 20 as 1 to 3. It may then be concluded that about three-fourths of the light which formed the spectrum of the umbra was really due to the umbra of the spot.

There were several bright granules on the umbra, but the spectra of these were seen distinct from that of the umbra. Each bright point as it came upon the slit gave a narrow spectrum like a bright thread extending along the dark spectrum of the umbra.

There still remained two sources of uncertainty. 1. In consequence of the mode in which the spectrum is formed, under similar conditions of the instrument, the dark lines should appear rather thicker when the light is feebler. 2. The increased thickness of the lines in the compound spectrum might be due to the light of the umbra, or to that of our atmosphere.

The uncertainty on both these points was removed by observing the feebler

spectrum of the illuminated atmosphere near the sun's limb. The lines in this spectrum, though they appeared very slightly stronger, were not so in a degree that could afford an explanation of the very marked increase of strength which most of them presented in the spectrum of the umbra. It seemed, therefore, satisfactorily determined that the light from the umbra had really suffered a more powerful absorption. The term umbra is used to include the cloudy stratum and the darker nucleus into which Mr. Dawes has shown the umbra of a spot may be usually resolved. It is probable that nearly the whole of the light under examination came from the part of the umbra known as the cloudy stratum. It was not possible to distinguish the spectra of these portions of the umbra.

The spectroscope was sufficiently powerful to show all the lines which are given in Kirchhoff's maps.

I carefully examined the spectrum of the umbra with that of the adjoining parts of the solar surface from A to G, but I was not able to detect any line of absorption in the spectrum of the umbra which was not also present in that of the sun's normal surface, or that any ordinary solar line was wanting in that of the umbra.

The increase of thickness, however, did not appear to take place in the same proportion for all lines. The lines C and F, due to hydrogen, appeared increased but very slightly, if indeed they were any thicker than would be due to a spectrum of feebler intensity. I incline to the opinion that these lines are not sensibly altered.

There is a small group of lines a little less refrangible than b , at 1601 to 1609 of Kirchhoff's scale, and which in his map are marked as coincident with lines of chromium, which was especially noticeable from increased thickness. That this circumstance was not connected with any peculiarity of the spot under examination is shown by a similar observation having been made on other spots.

Fig. 42 represents the appearance of the double line D in the spectrum of the umbra. The line nearly central between the two lines may be due, in part at least, also to sodium.* These lines appeared slightly broader, as if by the addition of a faint and narrowed nebulosity at both edges.

The group of lines at B are stronger, also b and E. Many of the lines marked in Kirchhoff's map as coincident with iron appeared much stronger in the spectrum of the spot.

The absence of sensible increase in F was marked in comparison with a

* The spectrum of the sodium at a high temperature is much more complex than was supposed. In addition to the three double lines besides D and a nebulous band, described in my paper "On the Chemical Elements," *Phil. Trans.*, 1864, p. 147, there is a line nearly central between the lines D. It is possible there may be also other lines in the interval between the strong lines D_1 and D_2 .

line or lines which were very strong, situated at a little distance on the less refrangible side of F—probably those of 2066·2 and 2067·1 of Kirchhoff's map.

It may be well to consider some of the conditions of the solar surface by which the phenomena observed may have been produced. A cooler state of the heated vapours, by which the lines of absorption are produced, would diminish the radiation from the gas itself, and so leave more completely uncompensated the absorption by the gas of the light from behind it. This cause would produce increased blackness of the lines, but would not account for more than a slight apparent increase of breadth. The greater breadth of the lines seems to point rather to a condition of the gases in which their power of absorption embraces for each line an increased range of wave-length. That the power of absorption of gases varies in this respect is shown by the increase of breadth which some of the bright lines of some gases assume under altered conditions of tension and temperature. It will be sufficient to refer to the expansion of the lines of hydrogen as the tension increases. A similar increase



Fig. 42.—SPECTRUM OF A SUN-SPOT.

in the range of its power of absorption on light passing through it should take place under similar conditions of density and temperature.

The phenomena may point to an increase of density in the vapours existing within the umbra. Such a state of things would necessarily exist at a point somewhat nearer the sun's centre; but we do not know through how great a depth of gas below the photosphere we receive the light which comes from the umbra. Our views on this point will be connected with the interpretation we give to Mr. Dawes's discovery of the existence within the umbræ of spots of a still darker part almost wholly devoid of light. Does this nucleus represent a more complete unveiling of the inner part of the sun? or does it show a still cooler and less luminous part of the down-rushing solar atmosphere? The latter suggestion, which is in accordance with the explanation of sun-spots proposed by Dr. Balfour Stewart, would seem to connect a lower temperature with the broader lines of absorption.

Some information might be gained if we could view the spectra of the

dark pores of the solar surface—an observation which is perhaps not impossible, since these pores are of varying degrees of darkness, and are probably due to conditions of the solar substance beneath the photosphere, similar to those which exist in the less normal phenomenon of sun-spots.

Mr. Lockyer's observations and my own would seem to show that probably no considerable part of the light which emanates from the umbra of a spot is due to luminous gas. It does not appear to me that this negative evidence is of great weight as to the complete absence of light in the umbra from such a source. The luminous gas would almost certainly emit light of the same refrangibility as some of the dark lines of the solar spectrum; and if there existed above the spot the vapours of the same substances in a cooler state, the light might be wholly absorbed, and the feebler emanations of the still luminous but cooler vapours might not do more than render somewhat less intense the dark gaps produced by the vapours in the stronger light of all refrangibilities which is evidently present.

What may be the source of the light which gives the continuous spectrum of the umbra we know not. It is not impossible that the dense and intensely heated gases, which probably form the inner substance of the sun, may in some cases emit lines so greatly expanded as to form, when numerous spectra are superposed, a sensibly continuous spectrum. In addition to this consideration, Dr. B. Stewart has suggested that, as gases possess a power of *general* absorption of light, a heated mass of gas, if sufficiently dense to be opaque, or partly so, would give a continuous spectrum as well as the spectrum of bright lines peculiar to it. It may be that, notwithstanding the high temperature, some substances may exist in the liquid state in consequence of the pressure produced by the sun's mass.

A POSSIBLE METHOD OF VIEWING THE RED PROMINENCES WITHOUT AN ECLIPSE

(From "Report of my Observatory," *Monthly Notices*, vol. xxviii., p. 88, February 1868)

"DURING the last two years Mr. Huggins has made numerous observations for the purpose of obtaining a view, if possible, of the red prominences seen during an eclipse. The invisibility of these objects at ordinary times is supposed to arise from the illumination of our atmosphere. If these bodies are gaseous their spectra would consist of bright lines. With a powerful spectroscope the light reflected from our atmosphere near the sun's edge would be greatly reduced in intensity by the dispersion of the prisms, while the bright lines of the prominences, if such be present, would remain but little diminished

in brilliancy. This principle has been carried out by various forms of prismatic apparatus and also by other contrivances, but hitherto without success."

ON A POSSIBLE METHOD OF VIEWING THE RED FLAMES
WITHOUT AN ECLIPSE

(From *Monthly Notices R.A.S.*, vol. xxix., p. 4, 1868)

My object in this note is to describe one of the "other contrivances" mentioned in the Report. The apparatus consisted of a number of screens of coloured glasses and other absorptive media, by which I was able to isolate portions of the spectrum. It appeared highly probable that if the parts of the spectrum which then alone remained were identical with those in which the bright lines of the flames occur, these objects would become visible.

For this inquiry I obtained a great variety of coloured glasses and other absorptive media. I first examined them with a prism to learn the absorptive power which they exercised on different parts of the spectrum. I then combined them in various ways. These glasses were sometimes employed before the eye, but more frequently by projecting the image of the sun's edge upon a screen, after the light had been sifted by the coloured media. In making these experiments means were taken that the whole of the sun's image should be got rid of, in order that the eye, kept in comparative darkness, might be more sensitive to the greatly feebler illumination of the objects sought for. As I had no knowledge of the positions in the spectrum of the bright lines, it would have been by accident only if I had succeeded in obtaining a view of the flames.

Now that the positions of these lines are known, this method appears to be very promising. Perhaps the light about the red line at C will be most easily isolated. I have a deep ruby glass which cuts off all the spectrum except the extreme red. I have since the eclipse observations only been able to make one attempt, when the state of the atmosphere was very unfavourable.

It is obvious that by this method the form and appearance of these flames could be observed and the objects measured with accuracy.

FROM A NOTE IN THE *MONTHLY NOTICES*, NOVEMBER 1869

(From *Monthly Notices R.A.S.*, vol. xxx., p. 36, 1869)

DURING the early part of the present year I tried a large number of coloured media. The difficulty is to combine two media which shall absorb all light of all refrangibilities except precisely that of the line C or the line F. If even

a small range of refrangibility besides that of the line selected, say C, be allowed to pass, the scattered light of the atmosphere overpowers and eclipses the prominences.

The most promising media of those which I tried was a solution of carmine in ammonia, which cuts off all the light more refrangible than C, combined with a solution of chlorophyll, which gives a strong band of absorption, taking away the brighter part of the light less refrangible than C. Unfortunately, however, the chlorophyll band encroaches a little upon C, and so weakens the light of the prominences. The absorption of chlorophyll, as Professor Stokes has shown, can be moved a little in the spectrum by acids and alkalies, and differs slightly in different plants; but I have not been able to degrade the band sufficiently to allow light of the refrangibility of C to pass wholly unimpaired.

NOTE ON A METHOD OF VIEWING THE SOLAR PROMINENCES
WITHOUT AN ECLIPSE

(From *Proc. Roy. Soc.*, vol. xvii., p. 302, 1869)

LAST Saturday, February 13, I succeeded in seeing a solar prominence so as to distinguish its form. A spectroscope was used; a narrow slit was inserted after the train of prisms before the object-glass of the little telescope.* This slit limited the light entering the telescope to that of the refrangibility of the part of the spectrum immediately about the bright line coincident with C.

The slit of the spectroscope was then widened sufficiently to admit the form of the prominence to be seen. The spectrum then became so impure that the prominence could not be distinguished.

A great part of the light of the refrangibilities removed far from that of C was then absorbed by a piece of deep ruby glass. The prominence was then distinctly perceived, something of this form.

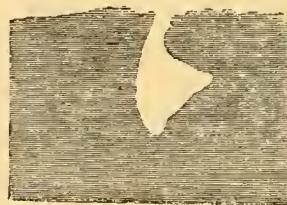


Fig. 43.

A more detailed account is not now given, as I think I shall be able to modify the method so as to make the outline of these objects more easily visible.

* See correction, in following note, of the place of the second slit.

NOTE ON THE WIDE-SLIT METHOD OF VIEWING THE SOLAR PROMINENCES

(From *Proc. Roy. Soc.*, vol. xxi., p. 127, 1873)

WHEN editing the English translation of Schellen's "Spectrum Analysis," I discovered that the short account of the method of viewing the forms of the solar prominences by means of a wide slit, which I had the honour of presenting to the Royal Society on February 16, 1869,* does not agree exactly in one respect with the account of the observation of February 13 as it was entered at the time in my Observatory book. The short note was written at the suggestion of a friend during a Committee held in the Royal Society's Apartments, and, as the concluding words show, was intended to be followed by a more detailed account of the method of observation. The point in question relates to the position of a second slit which was used to screen the eye from every part of the spectrum except that under observation. The words in my book written at the time are, "narrow slit found to be best at focus of little telescope with positive eyepiece." In the note the second slit was stated to have been placed before the object-glass of the little telescope. Such an arrangement was tried in connection with some other experiments in progress at the time. The plan of limiting the field of view to the part of the spectrum corresponding to the refrangibility of the light of the prominence, as well as the employment of a ruby glass, is of value when the air is not favourable, or when a spectroscope of small dispersive power is used.

ON A METHOD OF PHOTOGRAPHING THE SOLAR CORONA WITHOUT AN ECLIPSE

(From *Proc. Roy. Soc.*, vol. xxxiv., p. 409, 1882)

PROBLEMS of the highest interest in the physics of our sun are connected, doubtless, with the varying forms which the coronal light is known to assume; but these would seem to admit of solution only on the condition of its being possible to study the corona continuously, and so to be able to confront its changes with the other variable phenomena which the sun presents. "Unless some means be found," says Professor C. A. Young, "for bringing out the structures round the sun which are hidden by the glare of our atmosphere, the progress of our knowledge must be very slow, for the corona is visible only about eight days in a century, in the aggregate, and then only over narrow strips on the earth's surface, and but from one to five minutes at a time by any one observer." †

* *Proc. Roy. Soc.*, vol. xvii., p. 302.

† "The Sun," p. 239.

The spectroscopic method of viewing the solar prominences fails, because a large part of the coronal light gives a continuous spectrum. The successful photograph of the spectrum of the corona taken in Egypt, with an instrument provided with a slit, under the superintendence of Professor Schuster during the solar eclipse of May 17, 1882, shows that the coronal light as a whole—that is, the part which gives a continuous spectrum, as well as the other part of the light which may be resolved into bright lines—is very strong in the region of the spectrum extending from about G to H. It appeared to me, therefore, very probable that by making exclusive use of this portion of the spectrum it might be possible under certain conditions, about to be described, to photograph the corona without an eclipse.

In the years 1866-68 I tried screens of coloured glasses and other absorptive media, by which I was able to isolate certain portions of the spectrum, with the hope of seeing directly, without the use of the prism, the solar prominences.* I was unsuccessful, for the reason that I was not able by any glasses or other media to isolate so very restricted a portion of the spectrum as is represented by a bright line. This cause of unsuitableness of this method for the prominences, which give bright lines only, recommends it as very promising for the corona. If by screens of coloured glass or other absorptive media the region of the spectrum between G and H could be isolated, then the coronal light, which is here very strong, would have to contend only with a similar range of refrangibility of the light scattered from the terrestrial atmosphere. It appeared to me by no means improbable that under these conditions the corona would be able so far to hold its own against the atmospheric glare, that the parts of the sky immediately about the sun where the corona was present would be in a sensible degree brighter than the adjoining parts where the atmospheric light alone was present. It was obvious, however, that in our climate and low down on the earth's surface, even with the aid of suitable screens, the addition of the coronal light behind would be able to increase but in a very small degree the illumination of the sky at those places where it was present. There was also a serious drawback from the circumstance that, although this region of the spectrum falls just within the range of vision, the sensitiveness of the eye for very small differences of illumination in this region near its limit of power is much less than in more favourable parts of the spectrum—at least, such is the case with my own eyes. There was also another consideration of importance: the corona is an object of very complex form, and full of details depending on small differences of illumination, so that even if it could be glimpsed by the eye, it could scarcely be expected that observations of a sufficiently precise character could be made to permit of the detection of the more ordinary changes which are doubtlessly taking place in it.

* *Monthly Notices R.A.S.*, vol. xxviii., p. 88, and vol. xxix., p. 4.

These considerations induced me not to attempt eye-observations, but from the first to use photography, which possesses extreme sensitiveness in the discrimination of minute differences of illumination, and also the enormous advantage of furnishing a permanent record from an instantaneous exposure of the most complex forms. I have satisfied myself by some laboratory experiments that under suitable conditions of exposure and development a photographic plate can be made to record minute differences of illumination existing in different parts of a bright object, such as a sheet of drawing paper, which are so subtle as to be at the very limit of the power of recognition of a trained eye, and even, as it appeared to me, those which surpass that limit.

My first attempts at photographing the corona were made with photographic lenses; but uncertainty as to the state of correction of their chromatic aberration for this part of the spectrum, as well as some other probable sources of error which I wished to avoid, led me to make use of a reflecting telescope of the Newtonian form. The telescope is by Short, with speculum of 6 inches diameter and about $3\frac{1}{2}$ feet focal length. A small photographic camera was fastened on the side of the telescope tube, and the image of the sun after reflection by the small plane speculum was brought to focus on the ground glass. The absorptive media were placed immediately in front of the sensitive film, as in that position they would produce the least optical disturbance. Before the end of the telescope was fixed a shutter of adjustable rapidity which reduced the aperture to 3 inches. This was connected with the telescope tube by a short tube of black velvet for the purpose of preventing vibrations from the moving shutter reaching the telescope. On account of the shortness of the exposures it was not necessary to give motion to the telescope.

It was now necessary to find an absorptive medium which would limit the light received by the plate to the portion of the spectrum from about G to H. There is a violet (pot) glass made, which practically does this. I had a number of pieces of this glass ground and polished on the surfaces. Three or four of these could be used together, castor oil being placed between the pieces to diminish the reflection of light at their surfaces. Some inconvenience was found from small imperfections within the glass, and it would be desirable in any future experiments to have a larger supply of this glass, from which more perfect pieces might be selected.

In my later experiments I used a strong and newly made solution of potassic permanganate, in a glass cell with carefully polished sides. This may be considered as restricting the light to the desired range of wave-length, since light transmitted by this substance in the less refrangible parts of the spectrum does not affect the photographic plates.

Different times of exposure were given, from so short an exposure that the sun itself was rightly exposed, to much more prolonged exposures, in which

not only the sun itself was photographically reversed, but also the part of the plates extending for a little distance from the sun's limb. Gelatine plates were used, which were backed with a solution of asphaltum in benzole.

After some trials I satisfied myself that an appearance peculiarly coronal in its outline and character was to be seen in all the plates. I was, however, very desirous of trying some modifications of the method described, with the hope of obtaining a photographic image of the corona of greater distinctness, in consequence of being in more marked contrast with the atmospheric illumination.

Our climate is very unpropitious for such observations, as very few intervals, even of short duration, occur in which the atmospheric glare immediately about the sun is not very great. Under these circumstances I think it is advisable to describe the results I have obtained without further delay.

The investigation was commenced at the end of May of this year, and the photographs were obtained between June and September 28.

The plates which were successful are twenty in number. In all these the coronal form appears to be present. This appearance does not consist simply of increased photographic action immediately about the sun, but of distinct coronal forms and rays admitting in the best plates of measurement and drawing from them. This agreement in plates taken on different days with different absorptive media interposed, and with the sun in different parts of the field, together with other necessary precautions observed, makes it evident that we have not to do with any instrumental effect.

The plates taken with very short exposures show the inner corona only, but its outline can be distinctly traced when the plates are examined under suitable illumination. When the exposure was increased, the inner corona is lost in the outer corona, which shows the distinctly curved rays and rifts peculiar to it.

In the plates which were exposed for a longer time, not only the sun but the corona also is photographically reversed; and in these plates, having the appearance of a positive, the white reversed portion of the corona is more readily distinguished and followed in its irregularly sinuous outline than is the case in those places where the sun only is reversed, and the corona appears, as in a negative, dark.

Professor Stokes was kind enough to allow me to send the originals to Cambridge for his examination, and I have his permission to give the following words from a letter I received from him: "The appearance is certainly very corona-like, and I am disposed to think it probable that it is really due to the corona." Professor Stokes's opinion was formed from the appearance on the plates alone, and without any knowledge of their orientation.

I have since been allowed, through the kindness of Captain Abney, to compare my plates with those taken of the corona in Egypt during the eclipse of May last. Though the corona is undergoing, doubtless, continual changes,

there is reason to believe that the main features would not have suffered much alteration between May 17 and September 28, when the last of my plates was taken. This comparison seems to leave no doubt that the object photographed on my plate is the corona. The more prominent features of the outer corona correspond in form and general orientation, and the inner corona, which is more uniform in height and definite in outline, is also very similar in my plates to its appearance in those taken during the eclipse.

Measures of the average height of the outer and of the inner corona in relation to the diameter of the sun's image are the same in the eclipse plates as they are in my plates taken here.

There remains little doubt that by the method described in this paper, under better conditions of climate, and especially at considerable elevations, the corona may be successfully photographed from day to day with a definiteness which would allow of the study of the changes which are doubtless always going on in it. By an adjustment of the times of exposure, the inner or the outer corona could be obtained as might be desired. It may be that, by a somewhat greater restriction of the range of refrangibility of the light which is allowed to reach the plate, a still better result may be obtained.

Plates might be prepared sensitive to a limited range of light; but the rapid falling off of the coronal light about H would make it undesirable to endeavour to do without an absorptive screen. Lenses properly corrected might be employed, but my experience shows that excessive caution would have to be taken in respect of absolute clearness of the surfaces and of some other points. There might be some advantage in intercepting the direct light of the sun itself by placing an opaque disk of the size of the sun's image upon the front surface of the absorptive screen. Though for the reasons I have already stated I did not attempt eye-observations, there seems no reason why, with suitable screens and under suitable atmospheric conditions, the corona should not be studied directly by the eye. There might be some advantages in supplementing the photographic records by direct eye-observations. I regret that the very few occasions on which it has been possible to observe the sun has put it out of my power to make further experiments in these and some other obvious directions.

[I have Captain Abney's permission to add the following letter, this day received from him: "A careful examination of your series of sun-photographs, taken with absorbing media, convinces me that your claim to having secured photographs of the corona with an uneclipsed sun is fully established. A comparison of your photographs with those obtained during the eclipse which took place in May last, shows not only that the general features are the same, but also that details, such as rifts and streamers, have the same position and form. If in your case the coronal appearances be due to instrumental causes, I take

it that the eclipse photographs are equally untrustworthy, and that my lens and your reflector have the same optical defects. I think that evidence by means of photography of the existence of a corona at all is as clearly shown in the one case as in the other."—December 15, 1882.]

ON SOME RESULTS OF PHOTOGRAPHING THE SOLAR CORONA WITHOUT AN ECLIPSE

(From *Report Brit. Assoc.*, 1883, p. 351)

[The early part of this paper is omitted, as it is mainly a re-statement of the preceding one, "A Method of Photographing the Solar Corona without an Eclipse.]

. . . During the summer about fifty photographs have been obtained, which show photographic action about the sun of a more or less coronal character.

I placed these plates in the hands of Mr. Wesley, who has had very great experience in making drawings from the photographs taken during several solar eclipses, with the request that he would make a drawing for each day on which sufficient photographs had been taken, combining the results of the different photographs in one drawing. This was desirable, as whenever a sufficient duration of sunshine permitted, photographs were taken on silver chloride films, as well as on silver bromide plates; some photographs were taken with the sun screened by the brass disk, others without it; also photographs were taken with the sun in different positions of the field. As a rule, Mr. Wesley has introduced into his drawings those coronal features only which are common to all the plates taken on that day.

The apparatus is attached to the refractor of the equatorial in such a way that the direction of the length of the plate is in that of a parallel of declination; a line, therefore, across the plate is in a direction north and south, and from the date of the photograph the angle of position of the sun's axis can be found. On Mr. Wesley's drawings the orientation is marked, as well as the position of the sun's axis. Four drawings accompany this paper. In most of the negatives more structure than is shown in the drawings is suspected when the plates are carefully examined.

I regretted greatly that on May 6, the day of the solar eclipse, the sky here was very unfavourable. Up to the time of writing this paper I have not seen the photographs taken during the eclipse. Mr. Wesley wishes me to state that he has not seen the photographs or any drawings of the eclipse, and that therefore he has been wholly without bias in making his drawings from my plates. If these drawings are compared with the photographs taken during the eclipse, it should be borne in mind that the absence of sky illumination during

the eclipse would allow a larger part of the fainter and more distant regions of corona to be photographed, and that any peculiar conformations or detailed structure of these outer portions could not be expected to be seen on my plates.

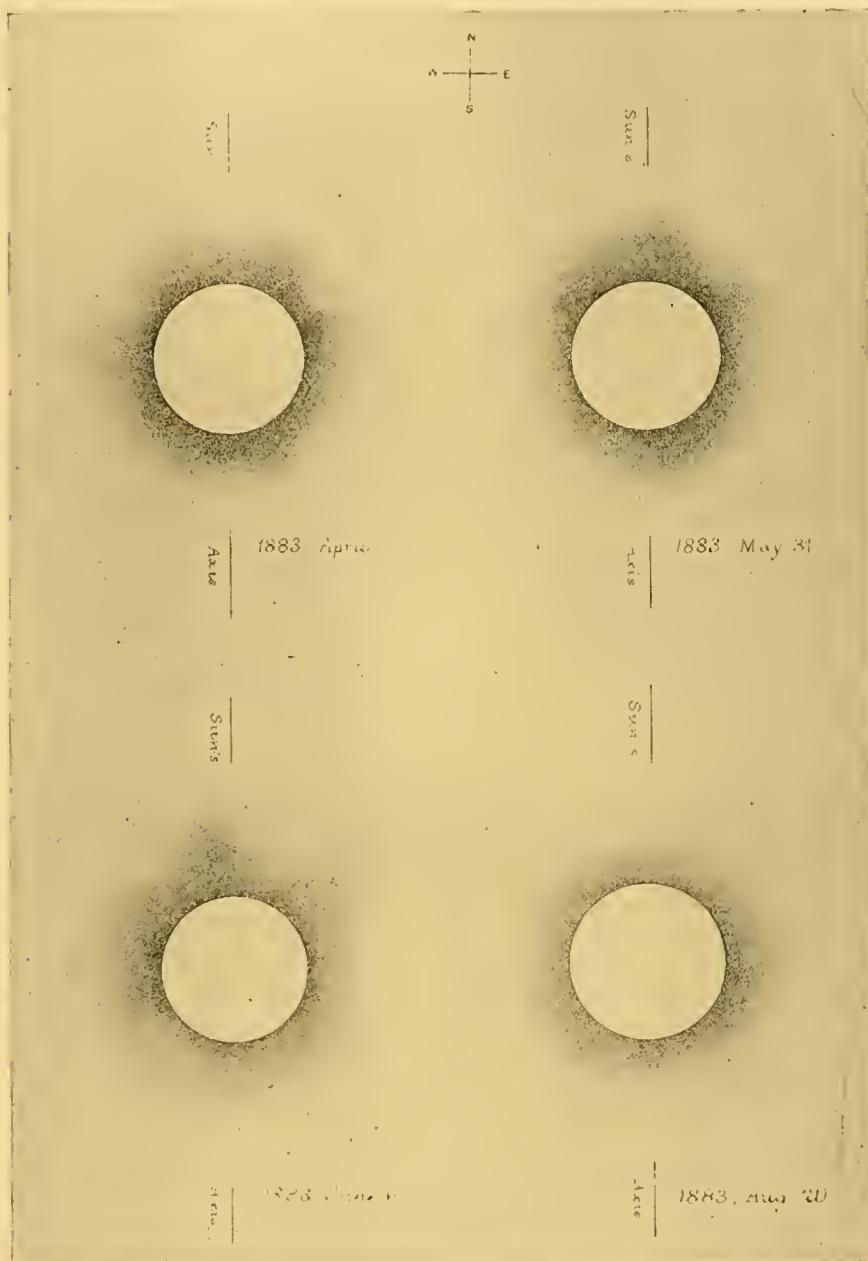


Fig. 44.—CORONA WITHOUT AN ECLIPSE.

P.S.—Messrs. Lawrence and Woods, the observers sent out at the expense of the Government to photograph the eclipse of May last at Caroline Island, have compared Mr. Wesley's drawings, and the original negatives from which

they were made, with the photographs taken during the eclipse. Mr. Lawrance, in a letter to Professor Stokes, dated September 14, 1883, says :—

“ Dr. Huggins called upon Mr. Woods this morning and showed us the drawings Mr. Wesley has made of his coronas. He told us that he particularly

did not wish to see our negatives, but that he would like us to compare his results with ours. We did so, and found that some of the strongly marked details could be made out on his drawings, a rift near the north pole being especially noticeable ; this was in a photograph taken on April 3, in which the detail of the northern hemisphere is best shown, while the detail of our southern hemisphere most resembles the photograph taken on June 6 : in fact, our negatives seem to hold an intermediate position. Afterwards I went with Dr. Huggins and Mr. Woods to Burlington House to see the negatives. The outline and distribution of light in the inner corona of April 3 is very similar to that on

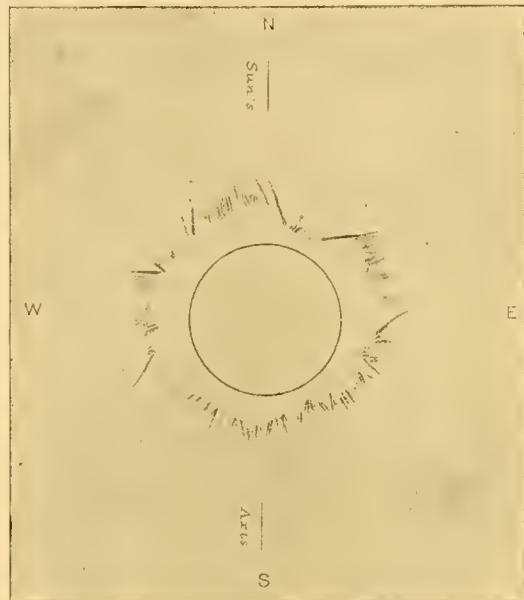


Fig. 45.—CORONA, TOTAL ECLIPSE MAY 6, 1883.

Drawing by Wesley.

our plate which had the shortest exposure ; the outer corona is, however, I think, hidden by atmospheric glare. As a result of the comparison, I should say that Dr. Huggins' coronas are certainly genuine as far as 8' from the limb.”

NOTE ON THE METHOD OF PHOTOGRAPHING THE CORONA WITHOUT AN ECLIPSE

As it seemed very desirable to test this method of attacking the corona at some place of high elevation, where the large part of the glare due to the lower and denser parts of our atmosphere would not be present, by the aid of a small grant from the Government fund at the disposal of the Royal Society, Mr. Ray Woods was sent to the Riffel, near Zermatt, in July 1884.

Fine matter of some kind—volcanic dust still remaining in the upper air from the Krakatoa eruption possibly, or it might be ice spicules—was always present, and Mr. Woods did not get once a really fine day. Nevertheless there were some appearances on the plates which might possibly be due to the corona.

Under these circumstances it was arranged that Mr. Woods should go to the Cape of Good Hope, and take daily photographs at the Royal Observatory

under the direction of Sir David Gill. These photographs were not successful; they showed no features which could be reasonably attributed to the corona.

There seems increasing evidence that the brightness of the corona is variable (p. 329; Fabry, *Compt. R.*, cxli., p. 870; and Perrine, *Lick Bull.*, 153); also it is certain that the scattering power of our atmosphere varies greatly at different times. Under the united favourable conditions of a bright corona and a very pure sky, the ratio of brightness of the corona to that of the air-glare before it might greatly exceed its value on ordinary occasions.

It appears to me of some scientific interest to give in full the complete history of these attempts to photograph the corona without an eclipse. (1909.)

THE BAKERIAN LECTURE—"ON THE CORONA OF THE SUN"

(From *Proc. Roy. Soc.*, vol. xxxix., p. 108, 1885)

Περὶ δὲ τὸν χρόνον, ὃν ἐν τῇ Ἑλλάδι ἐνεσπούδαζεν, ἐπεῖχε τὸν οὐρανὸν διοσημίᾳ τουαύτῃ, τὸν τοῦ Ἡλίου κύκλον περιελθῶν στέφανος, ἐοκὼς Ἰριδί, τὴν ἀκτῖνα ἡμαυροῦ.

PHILOSTRATUS, "Life of Apollonius," Bk. VIII., ch. xxiii. (ed. Leipzig, 1709).

'Αλλὰ περιφαίνεται τις αὐγὴ περὶ τὴν ἵτων, οὐκ ἔωστα βαθεῖαν γίνεσθαι τὴν σκιὰν καὶ ἄκρατον.

Plut. Opera, Mor. et Phil., vol. ix., p. 682 (ed. Leipzig, 1778).

THE sun is the only star the corona of which we have been able to observe, for all other stars are too distant to give true images in the telescope. If the sun were removed to a distance equal to that of the nearest star, its disk would subtend less than the one-hundredth of a second of arc. We have also to consider the small relative brightness of the corona, the light from which has been estimated at different times to be from $\frac{1}{100000}$ to about the $\frac{1}{400000}$ part of the sun's light. It is, indeed, possible that stars which have a higher temperature than our sun are surrounded by coronæ of greater extent and brightness.

At the eclipse of 1882, some information was obtained of the sun's condition in relation to that of the brighter stars. The photographs of the more refrangible part of the spectra of stars, which I had the honour to lay before this Society in 1879,* gave a clue by which the stars could be arranged in a serial order, at the head of which stand the bright stars Vega and Sirius. I ventured to suggest that the differences in their spectra might be due primarily to temperature; and even to make the further suggestion, that the hotter stars were probably the younger stars, and that we had obtained possibly some indications of the relative ages of the stars. The position of the sun came some distance down in the series, very near the position of Capella, and just above the stars which begin to show a yellow tinge in their light. In the ordinary solar spectrum it is difficult to distinguish the ultra-violet group

* *Proc. Roy. Soc.*, vol. xxx., p. 20; also *Phil. Trans.*, vol. clxxi., p. 66.

of hydrogen lines, upon the character of which this serial arrangement was mainly based, but in the photograph of the spectrum of the corona obtained during the Egyptian eclipse, Captain Abney and Professor Schuster have been able to recognise very thin bright lines corresponding to the lines of this group.* These lines were not due to the corona, but to prominences at the base of the corona. The thin condition of these lines, as well as the breadth of the lines of calcium at H and K, confirms the position which I had ventured to give to the sun relatively to some of the brighter stars—namely, as belonging to the least fervid of the white stars, and just above those which begin to show a yellow light.

There are indeed some stars in the spectra of which the line D₃, which is seen in the prominences and in the lower parts of the corona of the sun, appears as a bright line, but this may be due to gas below any true corona, which may be about these stars.

There are also the so-called nebulous stars, which are surrounded by an aureole of faint light of measurable angular extent, but it would seem more probable that these belong to, and should be discussed with, the clusters and nebulae, and should not be regarded as exhibiting a corona of the nature of that which surrounds the sun.

So far, then, as our present powers of observation go, the corona of the sun stands alone; it is therefore the more to be regretted that the observations of this object are beset with great and peculiar difficulties. The absorption and scattering of the sun's light by our atmosphere, amounting according to Professor Langley to nearly 40 per cent.,† which are essential to the maintenance of the conditions under which life, as it now exists, is possible upon the earth, comes in, in this case, so seriously to our disadvantage that the corona can be seen for a few minutes only at long intervals. It is only on the rare occasions when the moon coming between us and the sun cuts off the sun's light from the air at the place where the eclipse is total, that we can see the corona through the cone of unilluminated air which is in shadow. On an average once in two years, for from three to six minutes, the corona is visible, and then only over a very narrow strip of the earth's surface. It is not surprising that many attempts have been made to observe the corona without an eclipse. The earlier attempts were based upon the hope that if the eye were protected from the intense direct light of the sun, and from all light other than that from the sky immediately about the sun, the eye might become sufficiently sensitive to perceive the corona. In the later attempts, success has been sought for from the great diminution of air-glare which takes place at high elevations, when the denser and more dusty parts of the atmosphere are left below the observer. Professor Langley made observations on Mount Etna,

* *Phil. Trans.*, 1883, p. 267.

† *Amer. Journ. Science*, September 1884.

and also on Mount Whitney, 15,000 feet high. He says: "I have tried visual methods under the most favourable circumstances, but with entire non-success." Dr. Copeland, assistant to Lord Crawford, observed at Puno at a height of 12,040 feet. In his report he says: * "It ought to be mentioned that the appearances produced by the illuminated atmosphere were often of the most tantalising description, giving again and again the impression that my efforts were about to be crowned with success."

The spectroscopic method by which the prominences may be seen without an eclipse fails for the corona, because a small part only of the coronal light is resolved by the prism into bright lines, and of these lines no one is sufficiently bright and coextensive with the corona to enable us to see the corona by its light.

Let us look at some of the conditions of the problem. As the obstacle to our seeing the corona consists of the bright screen of illuminated air which comes in before it, it is of importance to consider the relative degree of brightness of the air-glare, under favourable conditions, to that of the corona behind it.

During the eclipse of 1878, Professor J. W. Langley found the apparent brightness of the coronal light at 1' from the limb of the moon to be six times greater than that of the full moon, but at 3' distance, the light to have fallen off to one-tenth of the light of the full moon. † Professor Harkness concludes for the same eclipse: (1) The total light of the corona was 3·8 times that of the full moon, or 0·0000069 of that of the sun. (2) The coronal light varied inversely as the square of the distance from the sun's limb. (3) The brightest part of the corona was 15 times brighter than the surface of the full moon. (4) The corona of December 12, 1870, seems to have been 7½ times brighter than that of July 29, 1878. ‡ In his report on the eclipse of 1883, M. Janssen says: "Cette expérience a montré qu'à Caroline l'illumination donnée a été plus grande que celle de la pleine lune." §

The chief point of importance for this inquiry lies not so much in the actual value of the coronal light as in the relation of that value to the brightness of the illuminated air near the sun. Many observers have borne testimony to the continued visibility of the corona for some minutes (from three minutes to twelve minutes) after the end of totality.

The observations which give to us direct information on this point are those which have been made of the planets Venus and Mercury when they come in between us and the sun. It is obvious that as the planet approaches the sun it comes in before the corona and shuts off the light which comes from it. Under these circumstances the observer sees the sky in front of the

* "Copernicus," vol. iii., p. 212.

† "Washington Observations: Reports of Solar Eclipses, 1878 and 1880," p. 214.

‡ *Ibid.*, p. 392.

§ "Annuaire pour l'An 1884," p. 875.

planet to be darker than the adjoining parts—that is to say, the withdrawal of the coronal light from behind has made a sensible diminution of the brightness of the sky. It follows that the part of the sky about the sun, behind which the corona is situated, and to which its light is added, is brighter than the adjoining parts, in a degree not far removed from the eye's power of distinguishing adjacent areas which differ by a small degree of brightness.

If, therefore, by any method of observation even a small advantage could be given to the coronal light as compared with the air-glare, and especially if, at the same time, we could by any method accentuate the small difference of illumination, a method might be found by which the corona could be observed.

When the report of the photographs taken during the Egyptian eclipse of 1882 reached this country, I was led to conclude that the coronal light as seen from the earth was strong in the violet, and probably to some extent also in the ultra-violet part of the spectrum.

Apart from the question of the greater relative intrinsic intensity of the more refrangible region of the coronal light as a whole, or of any one of its components (its gaseous component gave bright lines in the violet region), there are two considerations which show us that the coronal light should be strong in the violet as compared with the air-glare near the sun.

The selective absorption of our atmosphere would cause the light scattered by it in the near neighbourhood of the sun to be relatively poor in this part of the spectrum; but there is a second cause acting in the same direction, which arises from the selective power of absorption of the sun's atmosphere.

The absorption which the photospheric light suffers from the solar atmosphere has been investigated by Professor Langley, Professor Pickering, and especially with great minuteness by Professor H. C. Vogel. Vogel found that while at the edge of the sun's disk the red light was reduced to 30 per cent. of its value at the centre of the disk, the violet light was reduced to 13 per cent. Vogel sums up by saying that if the solar atmosphere were removed, the brightness of the violet part of the sun's light would be increased about three times, but the red light one and a-half times only.* The selective action would doubtless be more strongly marked beyond the visible limit.

The rapid increase of absorption near the sun's limb, in Vogel's observations, indicates a low and dense solar atmosphere. Professor Langley agrees in this view of the sun's atmosphere. He says: "The portion of the (sun's) atmosphere chiefly concerned in absorption, I have been led to believe, from several considerations, is extremely thin, and I am inclined to think is mainly identical with the reversing layer at the base of the chromosphere."

* "Spectralphotometrische Untersuchungen," *Monatsbericht der K. Ak. d. Wissenschaften*, Berlin, März 1877. Also "Ueber die Absorption der chemicalen wirksamen Strahlen in der Atmosphäre der Sonne," *ibid.*, Juli 1872.

Professor Hastings also considers the "layer which produces absorption to be very thin," but he prefers to regard this layer as consisting not of gas, but of "a thin smokelike envelope of precipitated material."* Professor Pickering assumes the existence of an absorbing atmosphere about equal in height to the sun's radius, but we shall see further on that there are reasons which make this supposition extremely improbable.

The light emitted by the corona, whether by the incandescent particles or by the gas mingled with them, which lies outside the low region of absorption, will not have been subjected to the same selective absorption as the photospheric light which is emitted below this region. For this reason the light emitted by the corona will be richer in the more refrangible rays than the sun's light before it enters our atmosphere, and will be in a still larger degree richer in these rays than the solar light which has been scattered by our atmosphere near the sun. These considerations led me to hope that if the corona were observed by this kind of light alone it would be at some advantage relatively to the air-glare which comes in before it. It was of importance at the same time to magnify the small advantage the coronal light might have by some method of observation which could bring out strongly minute differences of illumination. Such a power is possessed by a photographic surface. I took some pains to satisfy myself "that under suitable conditions of exposure and development a photographic plate can be made to record (strongly) minute differences of illumination existing in different parts of a bright object, such as a sheet of drawing-paper, which are so subtle as to be at the very limit of the power of recognition of a trained eye, and as it appeared to me, those which surpass that limit."†

In my early experiments I made use of coloured glass, or a cell containing a coloured liquid, for the purpose of isolating the violet part of the spectrum,‡

* "Constitution of the Sun," *Amer. Journ. Science*, vol. xxi., p. 33.

† *Proc. Roy. Soc.*, 1882, p. 411.

Professor Stokes has suggested the following method of increasing the intensity of that part of the coronal light which is polarised relatively to the glare from the sky. He says in a letter, which he permits me to add here: "The light of the corona is known to be strongly polarised, while the atmospheric glare would show no sensible polarisation. Let p be the intensity of the coronal light along any radius vector which is polarised radially, and q the intensity polarised tangentially, and let $2a$ be the intensity of the glare. Then, without polarising the light, the intensity of the coronal light relatively to the glare would be as $p+q$ to $2a$. Suppose now the light falling on the plate to be polarised, say, in a north and south plane. Then north and south the ratio of the coronal light to that of the glare would be increased to p to a , while in east and west directions it would be reduced to q to a . In north-east and south-west as well as in north-west and south-east directions, the ratio would be the same as without polarisation. If in four successive photographs the plane of polarisation were set to north, north-east, east, south-east, we should get a relative increase in coronal light, in one or other of the photographs, all round the sun. It would be least in north-north-east, east-north-east, etc., directions, where it would be $p \cos^2 22\frac{1}{2}^\circ + q \sin^2 22\frac{1}{2}^\circ$ to a , or about $0.85p + 0.15q$ to a .

"The most convenient way of polarising would probably be to use a Nicol of some size not far from the plate."

‡ *Ibid.*, vol. xxxiv., pp. 411, 412.

but afterwards I obtained the desired light-selection in the film itself by the use of argentic chloride, which Captain Abney had shown to be most strongly sensitive to light from λ to a little beyond H.* Plates prepared with argentic chloride possess a further advantage for this work in consequence of the greater steepness of their gradations of density corresponding to differences of light-action as compared with argentic bromide plates.

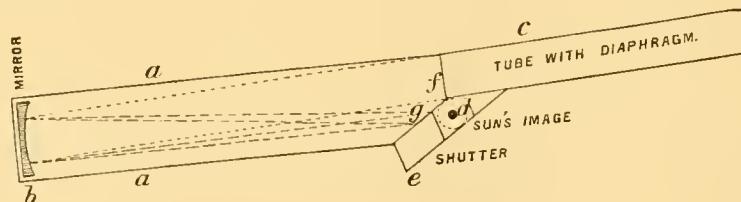
When very small differences of illumination only, existing close about a body so enormously bright as the sun, have to be photographed, the most minute precautions have to be taken to avoid false effects upon the plate, which may arise from several causes. Lenses should not be used to form the sun's image on the sensitive surface, in consequence of possible false light about the image which may come from outstanding aberrations, though they have been corrected for photographic work, and from reflections at the surfaces of the lenses. I therefore employed a mirror of speculum metal. Other necessary precautions are described in my paper: namely, the position of the shutter very near the focal plane; protecting the sensitive surface from the sun's direct light by a metal disk a little larger than the sun's image; placing before the apparatus a long tube fitted with diaphragms to prevent light from the sky, excepting near the sun, from entering the apparatus; backing the plates with asphaltum varnish; and some others.†

In my experiments in 1882 I used a Newtonian telescope by Short, but afterwards a fine mirror made by the late Mr. Lassell, which was so arranged that the image was formed directly upon the plate without reflection from a second mirror.‡

* *Proc. Roy. Soc.*, vol. xxxiii., p. 175.

† *Ibid.*, vol. xxxiv., p. 409, also *Report Brit. Assoc.*, 1883, p. 348. See also the photographic experiments of Dr. Lohse, *Vierteljahrsschrift Ast. Gesell.*, Bd. xv., S. 134. Dr. Lohse sums up an account of his methods and results thus: "Es gelang aber dieselben (die Schwierigkeiten) zu überwinden und Resultate zu erhalten, welche zu einer Fortsetzung der—hier freilich selten möglichen und mit grösserem Vortheil in möglichst hoher Lage anzustellenden—Experimenten ermuthigen."

‡ "I am indebted to Miss Lassell for the loan of a 7-foot Newtonian telescope made by the late Mr. Lassell. The speculum, which is 7 inches in diameter, possesses great perfection of figure, and still retains its original fine polish. I decided not to use more than $3\frac{1}{2}$ inches of the central portion of the speculum, partly for the reason that a larger amount of light would be difficult of management, and partly because this restriction of the aperture would enable me to adopt the arrangement which is shown in the diagram.



"It will be seen at once from an inspection of the diagram that in this arrangement the disadvantage of a second reflection by the small mirror is avoided, as is also the mechanical inconvenience of tilting the speculum within the tube as in the ordinary form of the Herschelian telescope. The

About twenty plates were taken in 1882, in all of which an appearance more or less coronal in character is to be seen about the sun's image. After a very critical examination of these plates, in which I was greatly helped by the kind assistance of Professor Stokes and of Captain Abney, there seemed to be good ground to hope that the corona had really been obtained upon the plates. On one plate especially forms resembling closely in character those present in the photographs of the eclipse of that year were visible.

In the following year, 1883, working with the Lassell mirror, I found that when the sky was free from clouds, but whity from a strong scattering of the sun's light, the sun's image in the photographs was well defined upon a sensibly uniform surrounding of air-glare, but without any such sudden increase of illumination near the sun's limb, or other indication which might be due to the corona. It was only when the sky was exceptionally clear that coronal appearances presented themselves with more or less distinctness.

The total solar eclipse of May 6, 1883, furnished an opportunity of comparing the photographs taken with an eclipsed sun with those taken in this country without an eclipse. On the day of the eclipse the weather was bad here, but plates taken before and after the eclipse were placed in the hands of Mr. Wesley, who had had much experience in making drawings from photographs taken during former eclipses. Mr. Wesley drew from these plates before any information reached this country of the results obtained at Caroline Island; he was, therefore, wholly without bias in the drawings which he made from them. When these drawings were compared afterwards with the Caroline Island plates, the general resemblance of the corona was strong, and the identity of the object photographed in England and at Caroline Island seemed placed beyond doubt by a remarkably formed rift on the east of the north pole of the sun, which is seen very nearly in the same position in the English plates

speculum *b* remains in its place at the end of the tube *a d*. The small plane speculum and the arm carrying it were removed. The open end of the tube is fitted with a mahogany cover. In this cover at one side is a circular hole, *f*, $3\frac{1}{4}$ inches in diameter, for the light to enter; below is a similar hole, over which is fitted a framework to receive the 'backs' containing the photographic plates, and also to receive a frame with fine-ground glass, for putting the apparatus into position. Immediately below, towards the speculum, is fixed a shutter, with an opening of adjustable width, which can be made to pass across more or less rapidly by the use of india-rubber bands of different degrees of strength. In front of the opening *f* is fixed a tube, *c*, 6 feet long, fitted with diaphragms, to restrict as far as possible the light which enters the telescope to that which comes from the sun and sky immediately around it. The telescope-tube, *a a*, is also fitted with diaphragms, which are not shown in the diagram, to keep from the plate all light except that coming directly from the speculum. It is obvious that, when the sun's light entering the tube at *f* falls upon the central part of the speculum, the image of the sun will be formed in the middle of the second opening at *d*, about 2 inches from the position it would take if the tube were directed axially to the sun. The exquisite definition of the photographic images of the sun shows, as was to be expected, that this small deviation from the axial direction, 2 inches in 7 feet, does not affect sensibly the performance of the mirror. The whole apparatus is firmly strapped on to the refractor of the equatorial, and carried with it by the clock motion."—*Report Brit. Assoc.*, 1883, p. 346.

and in those taken during the eclipse. This rift, slightly modified in form, was found to be present in a plate taken about a solar rotation-period before the eclipse, and also on a plate taken about the same time after the eclipse.*

In 1884, a grant from the fund placed annually by the Government at the disposal of the Royal Society was put into the hands of a committee appointed by the Council of the Royal Society for the purpose of photographing the corona at a place of considerable elevation. The Committee selected the Riffel, near Zermatt, which has an elevation of 8,500 feet, and appointed as photographer Mr. Ray Woods, who, as assistant to Professor Schuster, had photographed the corona during the eclipse of 1882, and who in conjunction with Mr. Lawrence had photographed the eclipse of the following year at Caroline Island.

Unfortunately during this year a very large amount of scattered light was always present about the sun, arising, it would seem, from finely-divided matter of some sort in the higher regions of the air. Mr. Woods observed from the Riffel that when no visible cloud or mist was present, there came into view a great aureole around the sun, about 44° in diameter, of a faint red colour at the outside and passing into bluish white near the sun. This was clearly a diffraction phenomenon showing the presence of minute particles of matter of some sort in the higher regions of our atmosphere.

The abnormally large amount of air-glare from this cause—even on the finest days—prevented any success in photographing the corona in this country, and went far to counteract the advantages of being above the denser strata of air which Mr. Woods would have gained on the Riffel under ordinary circumstances.

Mr. Woods sums up his results in the following words: “Results on the same day are almost, if not quite, alike both with the disk and without. The corona varies more or less from day to day. The clearer the day the better the results.” †

* *Report Brit. Assoc.*, 1883, p. 348, and Plates XI and XIa.

It seems desirable to put on record here a letter written by Mr. Lawrence to Professor Stokes, dated September 14, 1883: “Dr. Huggins called upon Mr. Woods this morning and showed us the drawings Mr. Wesley has made of his coronas. He told us that he particularly did not wish to see our negatives, but that he would like us to compare his results with ours. We did so, and found that some of the strongly marked details could be made out on his drawings, a rift near the north pole being especially noticeable; this was in a photograph taken on April 3, in which the detail of the northern hemisphere is best shown, while the detail of our southern hemisphere most resembles the photograph taken on June 6; in fact, our negatives seem to hold an intermediate position. Afterwards I went with Dr. Huggins and Mr. Woods to Burlington House to see the negatives. The outline and distribution of light in the inner corona of April 3 is very similar to that on our plate which had the shortest exposure; the outer corona is, however, I think, hidden by atmospheric glare. As a result of the comparison I should say that Dr. Huggins’ coronas are certainly genuine as far as 8' from the limb.”

† *The Observatory*, December 1884, p. 378.

During the last two years the sky in this country has been too bright from scattered light to make it possible to obtain successful photographs of the corona.*

We have now to discuss the probable nature of the corona.†

The drawings, but especially the photographs, of the solar eclipses of the last twenty-five years show that, notwithstanding great changes in form and in brightness, the corona is permanent in its more fundamental characters. The observed changes in form, in brightness, and in relative extension, are obviously due to secondary modifications of the conditions to which the corona owes its existence.

The circular form which was ascribed to the corona in the older observations can scarcely be regarded—even in the roughest sense of the word—as correct. On the contrary, the apparent form of the corona is always very irregular, in consequence of the greater extension and the greater relative brightness of certain parts. Upon the whole, there is an observed tendency of the brighter parts of the corona to assume a square form in consequence of the greater extension of the coronal matter at the latitudes between the poles and the equator of the sun—that is, over the zones of maximum spot-action. The corona is frequently less extended over the poles and over the equatorial regions of the sun.

A noticeable exception to this state of things occurred in 1878, when the most remarkable features of the corona were two extended equatorial rays which could be traced to a distance of several solar diameters. We shall have to consider, further on, some circumstances which may have had a large influence in bringing about this state of the corona.

In addition to these large changes in the external form of the corona, there is a complex structure within it which appears to be in continual change. This inner structure was observed by Professor S. P. Langley in 1878, under very favourable conditions, with a telescope of 5 inches aperture and a power of 50. He sums up his observations in the following words:‡

* It may not be unnecessary to state that what the photographer has to seize upon on his plates is the small excess of photographic power of the air-glare increased by the coronal light from behind over that of the air-glare alone. For this purpose the greatest care is necessary to select the most suitable time of exposure, and to arrest the slow development of the plate at the proper moment. Unless the attempt is made at a high elevation, the impression upon the plate must be a very slight one, and the developed image can only be seen under favourable conditions of illumination. Great care must be taken that all instrumental effects have been carefully eliminated. A convenient way of distinguishing effects upon the plate which are due to the instrument is to take pictures with the instrument alternately on the west and on the east side of the meridian. (See *Note* on p. 326. [1909].)

† The principal points of the discussion of the nature of the corona which follows were suggested in a discourse given at the Royal Institution, February 22, 1885, entitled "On the Solar Corona."

‡ "Report Total Solar Eclipse, 1878," Washington, p. 209.

1. Extraordinary sharpness of filamentary structure.
2. Arrangement not radial, or only so in the rudest sense.
3. Generally curved, not straight lines.
4. Curved in different directions.
5. Very bright close to the edge, fading out rapidly, fading out wholly (this part of corona) at 5' to 10' from it.

In addition to this more minute structure, there are large bright portions, apparently streaming outwards, and often leaving between them less bright spaces, which have the appearance of rifts. There are also curved forms which seem to turn round and return to the sun.

We must not forget that the corona has thickness as well as extension, and that the forms seen by us must appear more or less modified by projection. Rays inclined towards or from the observer would be materially altered in respect of their apparent position on the sun, and long rays in the nearer or more distant part of the corona would appear to start from parts of the sun other than those to which they really belong. For the same reason the increase of intrinsic brightness of the corona towards the sun's limb must be much less than the increase of brightness as seen by us, of which no inconsiderable part must be due to the greater extent of the corona in the line of sight as the sun is approached. Besides the real changes in the corona which have been observed at different eclipses, there are several sources of apparent change which may have modified the photographs taken of the corona. Of these may be mentioned—the state of the air at the time; the kind of sensitive surface employed; the length of exposure; whether the image has been formed by a lens which shortens and enfeebles the ultra-violet part of the light, or by a mirror which furnishes an image more truly representing the corona in the nature of the light existing in it. The difficulties which seemed to lie in the way of a satisfactory explanation of the forms and of the enormous extent of the corona, caused some doubts to be entertained as to the corona being a true solar appendage, and various views were formerly put forward to endeavour to explain the corona as an optical appearance only, arising from our atmosphere, from a lunar atmosphere, or from cosmical dust. Mr. De la Rue, in his address before Section A of the British Association in 1872, says truly, "The great problem of the solar origin of that portion of the corona which extends more than a million of miles beyond the body of the sun, has been, by the photographic observations of Colonel Tennant and Lord Lindsay in 1871, finally set at rest, after having been the subject of a great amount of discussion for many years." *

These earlier views are too completely a part of the history of the subject to need mention here, but for the circumstance that Professor Hastings has

* *Report Brit. Assoc., 1872*, p. 6.

recently revived the theory of Delisle, that the corona is an optical appearance due to diffraction.

Professor Hastings bases his theory upon the behaviour of the bright line 1474, which he saw, in his spectroscope, change in length east and west of the sun during the progress of the eclipse at Caroline Island in 1883. He assumes, in his explanation of this observation, that Fresnel's theory of diffraction may not apply in the case of a solar eclipse, and he suggests that at different moments the phases of the light-waves may change so that they no longer form a continuous periodic series, and that it is possible, at such great distances, that the interior of the shadow may not be entirely dark, and that sufficient light may come inside to give to an observer on the earth the appearance of a bright aureole around the moon.*

Professor Hastings considers the simpler explanation of his observation which has been suggested, that the change in length of the line which he observed might be due to a scattering by our air of the light from the brighter part of the corona, and therefore might not indicate any change in the corona itself during the progress of the eclipse, to be untenable, on the ground that the air was too clear, and "diffusion absolutely insensible." He supports this strong statement by saying that the photographs taken by the English and by the French observers showed a sensibly black moon, and that "in the photograph of the coronal lines H and K, taken by the English observers, these lines ended abruptly at the moon's edge."†

Captain Abney, F.R.S., who has the photographs taken at Caroline Island under examination, informs me that :

"The diffusion during that eclipse was not insensible, as the lines H and K are distinctly visible across the black moon as dark lines. It is true that H and K, as bright lines, do stop at the moon's limb, but these lines are not coronal lines, as they belong to the prominences. In the Egyptian eclipse—which was a very short one—the prominences were far over the moon's limb, and the diffusion due to the atmosphere was such that the lines H and K were shown as bright lines over the moon. In the Caroline Island eclipse the prominences were much less marked and more hidden during the eclipse than was the case in Egypt, and it appears that the diffusion by the air must have been much greater in the former (Caroline Island) than in the latter, since it is the light from the hidden sun which was evidently reflected and re-reflected. On one side of the moon's limb H and K are seen reversed, whilst on the other they are reversed beyond the bright lines."

"In both cases the reversals are rather faint, but as strong as the reversal which was seen on the corona spectrum at the Egyptian eclipse. In my

* "Report of Expedition to Caroline Island, 1883," Washington, p. 105.

† *Ibid.*, p. 107.

opinion, in the photographs of the corona with the longest exposure (I am not now speaking of spectrum photographs) the moon is not shown as perfectly black, but I should not like to found any theory very definite as to this, as it might be due to over-development, but I think not."

It should be mentioned that during the time that Professor Hastings observed the change in length of the line 1474, photographs of the corona were taken by M. Janssen, and by Messrs. Lawrence and Woods. M. Janssen says: "Les formes de la couronne ont été absolument fixes pendant toute la durée de la totalité."* The photographs taken by Messrs. Lawrence and Woods show that the corona suffered no such alterations in width and form as would be required by Professor Hastings' theory during the passage of the moon across the sun.

For other points raised by Professor Hastings, and for his discussion of former spectrum observations of the corona, I must refer to his memoir.[†]

The evidence in favour of the corona being a true solar appendage appears to me to be of overwhelming weight. It seems difficult on any other hypothesis to explain satisfactorily—(1) the observed and the photographed spectra of different parts of the corona; (2) the visibility of the planets Venus and Mercury as dark bodies when near the sun; (3) the filamentous, and especially the peculiar curved structures seen in photographs of the corona; (4) the close agreement of photographs taken at different times during an eclipse, and especially between photographs taken during the same eclipse at places many hundreds of miles apart.

At the same time a very small part of the light which is seen about the eclipsed sun must be due to diffusion by our atmosphere of the coronal light itself, especially of the very bright part near the sun's limb; and we have an indication of the amount of this diffused light from the apparent illumination of the dark moon, where the effects of diffusion will be most strongly present. During some eclipses the part of the sky where the sun and moon are may be faintly illuminated by light reflected from those regions of the atmosphere near the horizon which are still in direct sunlight.

It may be well to mention the principal hypotheses which have been suggested in explanation of the corona.

1. That the corona consists of a gaseous atmosphere resting upon the sun's surface and carried round with it.
2. That the corona is made up wholly or in part of gaseous and finely divided matter which has been ejected from the sun, or received by it, and which is in motion about the sun from the forces of ejection, of the sun's rotation, and of gravity, and possibly of a repulsion of some kind.
3. That the corona resembles the ring of Saturn, and consists of swarms

* *Annuaire pour l'An 1884*, p. 859.

[†] *Vide ante*.

of meteoric particles revolving with sufficient velocity to prevent their falling into the sun.

4. That the corona is the appearance presented to us by the unceasing falling into the sun of meteoric matter and of the débris of the tails of comets.

5. That the coronal rays and streamers are, at least in part, meteoric streams strongly illuminated by their near approach to the sun, neither revolving about nor falling into the sun, but permanent in position and varying only in richness of meteoric matter, which are parts of eccentric comet orbits. This view has been supported on the ground that there must be such streams crowding richly together in the sun's neighbourhood.

6. The view of the corona suggested by Sir William Siemens in his solar theory.*

The sun must be surrounded by a true gaseous atmosphere of relatively limited extent, but there are several considerations which forbid us to think of a solar atmosphere, in the proper sense of the term—that is, of a continuous mass of gas held up by its own elasticity, which rises to a height sufficient to afford an explanation of the corona which streams several hundred thousand miles above the photosphere.

Gravitation on the sun is about twenty-seven times as great as on the earth, and an atmosphere extending to a moderate coronal height, even if it consisted of a gas thousands of times lighter than hydrogen, would have more than metallic density at the sun's surface, a state of things which spectroscopic and other observations show cannot be the case.

There is another consideration from the rapid increase of density which would take place sunwards in such an atmosphere. Each stratum would be compressed by the weight of all the strata above it, and therefore in descending by equal steps the density of the atmosphere would increase in geometrical ratio. Professor Newcomb gives as an example an atmosphere of hydrogen; such a gas, though heated to as high a temperature as is likely to exist at a height of a hundred thousand miles above the sun, would double its density every five or ten miles.† There is no approach to so regular and so rapid an increase of density to be observed in the corona.

Another circumstance which puts a continuous gaseous atmosphere out of question is the fact that comets have passed unscathed through the coronal

* Since this lecture was read my attention has been called to the papers by Professor O. Reynolds, "On the Tails of Comets, the Solar Corona, and the Aurora considered as Electric Phenomena," and "On an Electrical Corona resembling the Solar Corona," in vol. v., 3rd Ser., *Mem. Lit. and Phil. Soc., Manchester*, pp. 44-56, and pp. 202-209. Professor Reynolds considers the solar corona to be a species of that action known as the electric brush, and to be well represented by discharging electricity from a brass ball in a partially exhausted receiver.

† "Popular Astronomy," p. 259.

regions. Shooting stars passing with the relatively small velocity of thirty or forty miles per second through our atmosphere, rarefied as it is at the height of fifty or sixty miles, are instantly burnt up. Resistance and heat increased as the square [or more probably for such high velocities as the cube*] of the velocity, yet the nucleus of a comet has passed through several hundred thousand miles of coronal matter with a velocity of three hundred miles per second without suffering any sensible loss of velocity. These considerations are amply sufficient to show that the theory of a solar atmosphere of gas of the extent of the corona held up by its own elasticity cannot be entertained.

As we have reason to believe that the corona is an objective reality about the sun, matter of some sort must exist wherever the corona is seen to extend. The questions before us are—(1) In what form does the matter exist? (2) Whence does it come? (3) What are the dynamical conditions under which it can exist at such great heights above the sun?

(1) On the first of these questions, as to the condition of the matter, the spectroscope has given us definite information. The spectrum of the corona is compound, and consists of three superposed spectra.

(a) A bright continuous spectrum, which informs us that it comes from incandescent solid or liquid matter.

(b) A solar spectrum, which shows that the incandescent solid or liquid matter of the corona reflects to us light from the photosphere.

(c) A spectrum of bright lines, which is relatively faint and varies greatly at different eclipses. We shall consider this spectrum more particularly further on; it is sufficient at this part of the argument that we speak of this spectrum so far only as it tells us of gaseous matter which accompanies the solid or liquid matter.

It is scarcely necessary to say that solid or liquid matter can exist in the corona only in the form of discrete particles of extreme minuteness.

The corona must, therefore, consist of a fog, in which the particles are incandescent, and in which the gaseous matter does not form a continuous atmosphere. Some of the considerations we have already had before us make it evident that this coronal fog, except very near the sun, must be of a degree of tenuity surpassing any experience we possess from terrestrial experiments. In order to give some definiteness to our conceptions, let us suppose a single minute liquid or solid particle in each cubic mile. A fog even so extremely attenuated, or even much more so, would probably be fully sufficient to give rise to the corona, under the enormous radiation to which it is subjected.

(2) The next question we have to consider is whether the matter of the corona is of solar origin, or whether it comes upon the sun from without.

* See Bashforth, *Phil. Trans.*, vol. clviii., p. 417.

Two external sources of the coronal matter have been suggested, and are widely held—namely, (a) meteoroids, and (b) the lost matter of the tails of comets.

(a) The solar system is crowded with meteoroids revolving in all kinds of erratic orbits, and we know that the earth encounters many thousands of them every hour, but the sun is in a different position with regard to such of these bodies as belong to our system. In order to fall into the sun the planetary meteoroids would have to be thrown into it, through some disturbance of their orbits produced by planetary attraction, or by collision with other streams, unless we admit a slow retardation of velocity produced by a resisting medium.

There may be meteoroids which fall directly into the sun from space. Mr. Denning's recent observations seem to show that the solar system encounters meteor streams which may be moving with great velocity through space.*

Many of these bodies may fall into the sun, but we have no knowledge of conditions which would ensure so steady an inflow of meteoroids as would be needed to maintain the observed extent of the corona in a state of permanence about the sun.

(b) The other suggestion which has been made regards the corona as fed by the lost matter of the tails of comets. We must remember that the matter which comes from the nucleus of a comet, and forms its tail, and is then lost, has been shown by the spectroscope to consist in nearly all comets of carbon, hydrogen, nitrogen, and possibly oxygen.† If this matter is condensed into the discrete particles which form the tail, in the same conditions of chemical combination as it existed originally in the nucleus, we should expect these particles to be again vaporised in their near approach to the sun; and under these conditions we should expect to find the corona to be mainly gaseous, and to give a spectrum similar to that which is produced by the emitted light of comets. We know that such is not the case; there is, however, a single observation by Tacchini at Caroline Island, in which in one part of the corona he suspected two of the bands which are present in the ordinary cometary spectrum. His words are: "Dans le spectre du grand panache, qui était faible et presque continu, et que l'on voyait seulement à fente large, j'ai observé deux bandes qui m'ont semblé être analogues à celles que j'ai observées dans les spectres de comètes, c'est-à-dire, la centrale et la moins réfrangible."‡ The terms in which this unique observation is given show that the lines, even if truly present, were faint and exceptional, and cannot be regarded as characteristic of the coronal light.

* *Monthly Notices R.A.S.*, vol. xlv., p. 93. See also subsequent papers.

† *Phil. Trans.*, 1868, p. 559, and *Proc. Roy. Soc.*, vol. xxxiii., p. 1.

‡ *Annuaire pour l'An* 1884, p. 862.

It may indeed be suggested that the cometary matter suffers decomposition at the time when it becomes luminous near the nucleus, and that carbon may be separated in a finely divided state, and go to form part of the lost matter of the tail. In the case of comets which have more than one tail, or exhibit rays driven off with a curvature different from that of the principal tail, there is good reason to believe, as Bredichin has endeavoured to show,* that each tail or caudal ray consists of matter different in density, which has been separated by a force of repulsion varying as the surface. It would appear doubtful, even on this view, if the supply of comets' tails is sufficiently regular in amount to maintain a permanent corona about the sun.

It seems to me to be much more probable that the corona is fed from the sun itself. This view is supported by the spectroscopic evidence, for the coronal gas is shown to consist of substances which exist also in the photosphere. The structure seen in the corona is much more in harmony with the view that the matter is going up from the sun than that it is coming down upon the sun.

An examination of the photographs taken at eclipses, or of Mr. Wesley's admirable drawings from them, can scarcely fail to lead an unbiassed student to the same conclusion as that which was forced upon Mr. Lewis Swift when he observed the corona of 1878: "I was irresistibly led to the conclusion that the corona, whatever may be its nature, is not a solar atmosphere, nor an inflow of meteoric matter, as many suppose, but rather an outflow of something."† These considerations appear to me to be of great weight in support of the view that, though some meteoroid and some cometary matter may fall into the sun, the corona consists essentially of matter coming from the sun.

(3) We have now to consider under what dynamical conditions matter coming from the sun can take on forms such as those we see in the corona, and can pass away to such enormous distances, in opposition to gravitation, which is so powerful at the sun.

There is another celestial phenomenon, very unlike the corona at first sight, which may furnish us with a clue to the true answer to this question. The head of a large comet presents us with luminous streamers and rifts and curved rays, which are not very unlike, on a small scale, some of the appearances which are always present in, and are peculiar to, the corona. We do not know for certain the conditions under which these cometary phenomena take place, but the only theory upon which they can be satisfactorily explained, and which now seems on the way to become generally accepted, attributes

* *Annales de l'Observatoire de Moscou*, and *Astronom. Nachrichten*, No. 2411.

† "Report Total Solar Eclipses of 1878 and 1880," Washington, p. 231.

them to electrical disturbances, and especially to a repulsive force acting from the sun, probably electrical, which varies as the surface, and not, like gravity, as the mass.* A force of this nature in the case of highly attenuated matter can easily master the force of gravity, and, as we see in the tails of comets, blow away this thin kind of matter to enormous distances in the very teeth of gravity.†

If such a force of repulsion, acting from the sun, is experienced by comets, it must also be present near the sun, and may well be expected to show its power over the matter ejected from the sun's surface.‡

The existence of a force, which, under suitable conditions, may become one of repulsion at the sun's surface, is not hypothetical only, for we have reasons to believe that such a force must really be present there. Though we have no definite knowledge of the distribution of electricity on the surface of the sun, we do know that chemical and mechanical actions are taking place there which must be accompanied by electrical disturbances. It seems to me that these disturbances, which must be of a high order of magnitude, bring about

* *Proc. Roy. Inst.*, vol. x., p. 9; also Bredichin, *Annales de l'Observatoire de Moscou*, vol. v., No. 2, p. 39; *Astronom. Nachrichten*, No. 2411; and papers by Faye in the *Comptes rendus*; Stokes, "On Light as a Means of Investigation," p. 70 *et seq.*; O. Reynolds, "On Cometary Phenomena," *Mem. Lit. and Phil. Soc., Manchester*, vol. v., p. 192.

† Euler's pressure of radiation, theoretically proved by Maxwell in 1873, had not then been experimentally established. (1909.)

‡ As a contribution to the history of opinions involving more or less distinctly the idea of repulsion, it may be well to give the following words by Professor Young (*Amer. Journ. Science*, vol. i., May, 1871, p. 7): "On the one hand, that of Professor Norton and Mr. Proctor, whose views regarding these rays (the long faint rays) are nearly identical, and represent them to be streams of matter, similar to cometary substance or auroral." In a footnote Professor Young says further: "Since my name has sometimes been referred to in connection with the so-called 'Auroral Theory of the Corona,' it is proper for me to state that I make no claim to be its originator. So far as I know, Professor Norton was the first to work out and publish a connected theory of the subject, basing his conclusions largely upon his discussions of Donati's comet, which were printed in this Journal some years ago. Professor Winlock also informs me that he has held and published a very similar opinion, and so I think have more than one of the European astronomers. My own father, more than twenty years ago, was accustomed to teach from the same chair of astronomy which I now occupy an essentially similar doctrine. Thus the idea had long been familiar to me, and, I presume, more or less so to astronomers generally."

It may be well to give a more direct reference to the papers of Professor W. A. Norton. He says, speaking of comets (*Proc. Amer. Assoc.*, 1854, p. 166): "The tails of comets flowing away under a repulsive force from the sun . . . [this repulsive force] to consist of the impulsive action of auroral matter flowing from the sun." Again, speaking of the corona, he says: "The aigrettes of auroral matter flowing off chiefly from the polar regions into space." In a subsequent paper (*Proc. Amer. Assoc.*, 1859, p. 167) Professor Norton defines his idea of the repulsive force as "a general force of cosmical repulsion exerted by all cosmical masses."

Mr. Proctor's views will be found in his work, "The Sun, the Ruler of the Planetary System," 3rd. ed., 1885, pp. 326-427.

For M. Faye's views on a repulsive force, see *Annuaire pour l'An* 1883, also *Annuaire pour l'An* 1885, and numerous papers in the *Comptes rendus*. Reference should also be made to the conjectures on the existence of a repulsive force thrown out by Sir John Herschel in his Cape Observations.

in some way the magnetic changes on the earth which are observed to take place in connection with solar phenomena.*

The grandest displays of terrestrial electrical disturbance must be altogether insignificant in comparison with the electrical changes which must accompany the ceaseless and fearful activity of the photosphere. Not to mention the frequent outbursts of heated gas thousands of miles high, and over areas in which the earth could be engulfed, there is the unceasing formation of the fiery photospheric cloud-granules about as large as Great Britain. Surely it is not too much to say that our terrestrial experience of lightning and of auroræ fail to supply us with any adequate basis for a true conception of the electric forces in action on the sun.

The phenomena of comets suggest not merely a highly electrical condition of the sun's surface, but also the permanence of an electric potential of the same kind, whether negative or positive.† Though we do not know enough of what is taking place at the sun to define the conditions which may cause the matter ejected from the sun's surface to have a high electric potential of the same name, yet we can see that broadly all the different actions which take place there, and to which the electric disturbances are probably due, are parts of one continuous process going on always in the same direction—namely,

* Professor Stokes and Professor Balfour Stewart have both speculated on the connection between solar disturbances and terrestrial magnetism, and have both imagined that the operative solar change is thermic—not electrical—and that it is through radiation that it affects the condition of the earth in such a manner as to be manifested by magnetic disturbances, though the modes in which these philosophers have conjectured that this takes place are wholly different. In a subsequent note I have suggested that the operative solar change is electrical, and that the action is probably one of statical induction.—August 20, 1885.

† The sun's potential may be regarded as due to actions of some kind always going on, or to a permanent charge received at some past time. The sun, if once charged with electricity of the same name, would doubtless remain so charged, as Mr. Crookes' experiments appear to show that a vacuum would be a perfect insulator.

If the sun has been charged with electricity of one name, we do not know how this came about, though more than one probable conjecture might be hazarded. Some facts mentioned further on as to the influence of Mercury and of Venus upon the coronal matter would seem to make it very probable that these planets are permanently charged with electricity of the other name to that of the sun. If this should hold good also of the more distant planets (we know nothing of the absolute potential of the earth's surface), we should have the planets charged with one kind of electricity and the sun charged with the opposite electricity. As we have reason to believe that the sun and the planets formed originally one cosmical mass, the question may be suggested whether these changes of electricity of opposite names can have been brought about in connection with the separation of the matter which forms the planets from that which exists in the sun.

If we regard the sun as possessing an electric potential of one name, it is not absolutely necessary to suppose the local electric disturbances which are spoken of in the text. Electric disturbances are undoubtedly taking place there, and through these the ejected matter might come to have a higher potential than it possessed as forming part of the sun. Through these local disturbances some of the matter of the corona might have sometimes a higher or lower potential of the same name, and in this way might arise one of the varying conditions upon which the observed changes in the corona depend.—August 20, 1885.

the transference of energy from the interior to the photosphere, and the loss of the energy there in the radiant form.

We must bear in mind that a strongly electrified state of the solar surface would not act as a force of repulsion upon discrete particles of matter insulated from each other, such as exist in the tails of comets and in the corona, unless these particles possessed an electric potential of the same kind as the solar surface. If these particles were in an unelectrified condition, the action of the sun would be one of statical induction only, altering the original distribution of electricity over their surfaces, but powerless to change in any sensible manner the positions of their centres of gravity in space, because the attraction on one side of each particle would be balanced by the repulsion on the other.

If we grant the existence of a high electric potential of the sun's surface, we become possessed of a means of explanation of the chief coronal phenomena, provided we accept the conclusion to which our arguments have already led us, that the matter of the corona is of solar origin.

The photosphere is the seat of ceaseless convulsions and outbursts of fiery matter. Storms of heated gas and incandescent hail rush upwards, or in cyclones, as many miles in a second as our hurricanes move in an hour. Dante's and Milton's poetic imaginings of Hades fall far below the commonplace scenes at the solar surface. Is it, then, going beyond what might well be to suppose that some portions of the photospheric matter, having an electric potential of the same kind as that of the solar surface from which they come, and ejected, as is often the case, with velocities not far removed from that which would be necessary to set them free from the sun's attraction, should come under the action of a powerful electric repulsion, and so be carried upwards and from the sun?

If we take this view of things, we are able to accept the objective reality of many of the very long coronal rays, which seem to rest upon sufficient testimony. At the eclipse of 1878 Professor Langley traced the coronal matter to a distance of twelve solar diameters, and he adds, "I feel great confidence in saying that (this distance) was but a portion of its extent."* Professor Newcomb traced this ray to about the same distance—"six degrees from the disk."† Such distances are small as compared with the extent of the tails of comets.

This view of the corona is in harmony with the source of the matter, and of the forces which the structure of the corona almost irresistibly suggests—namely, that these have their seat in the sun. We should expect, what we find to be the case, that there is usually great coronal richness and extension over the spot zones where the solar activity is most fervent. Matter blown upwards by an electrical repulsion would rise with the smaller rotational velocity

* "Report Total Solar Eclipse, 1878," Washington, p. 208.

† *Ibid.*, p. 104.

of the photosphere from which it started, and would appear to lag behind in its ascent, and so give rise to the curved rays which are so common a feature. We may well suppose that the forces of eruption and of subsequent electrical repulsion would vary in different places, and not be always strictly radial; under such circumstances a structure, similar to that which the corona presents, might arise. A force of repulsion would also be present among the similarly electrified particles of the corona acting in all directions, and would cause these particles to separate from each other during their ascent from the sun; the amount of this diffusion would depend upon several factors, among others, upon the original velocity of ascent, and upon the density and the degree of electric potential of the repelled stuff.

A relatively very small amount of matter, under this diffusing force, would suffice to give rise to the corona, and we can see how the extremely attenuated state of the corona, consisting as it must do of minute particles widely separated, it may be by miles each from the other, may have been rapidly brought about.

It is now time to consider the gaseous matter which we know to be associated with the coronal particles, but not to form a continuous gaseous atmosphere. The gas which exists with the incandescent particles, and which the spectroscope shows to have come from the photosphere, may have been carried up as gas, or have been in part distilled from the condensed matter which forms the coronal particles under the enormous radiation to which they are exposed. Such a view of the gas which is present in the corona would not be out of harmony with the circumstance that the amount of gas relatively to the incandescent particles appears to vary (at the last eclipse in Caroline Island it seems to have been but very sparingly present), nor with the very different heights to which different bright lines may be traced at different parts of the corona and at different eclipses. Gases of different vapour-density would be acted upon differently by an electric force of repulsion which varies as the surface, and would to some extent be winnowed from each other; the lighter the gas the more completely would it come under the sway of repulsion, and so would be carried more rapidly to a greater height than a gas more strongly held down by gravity. The relative proportions, as well as the actual amounts at different heights in the corona, of the gases which the spectroscope shows to exist there, would vary from time to time; they would depend in fact also on the largeness of supply from below—in other words, upon the state of activity of the photosphere—and in this way there would come about a relation probably between the corona and the prominences.

The varying amount of gas in different parts of the corona is illustrated by the following statement in the Report on the Eclipse of 1882 by Captain Abney and Professor Schuster:

"The ring in the green (1474) is particularly strong in the south-western

quadrant, and hardly visible at some other points of the sun's limb. The yellow ring (D_3) is much fainter on the whole, but more uniform all round the sun."

Further on (p. 270) they say: "As regards the corona, we may perhaps point out that hitherto the position of only one true coronal line had been fixed, though two other lines had been suspected. The corona during the late eclipse seems to have been especially rich in lines. Thollon observed some in the violet without being able to fix their position, and Tacchini could determine the position of four true coronal lines in the red; from the photograph we have been able to measure about thirty additional lines, thus increasing the number of lines considerably."*

Captain Abney informs me as follows: "The spectrum of the corona had fewer lines in the Caroline Island eclipse (1883) than in the Egyptian eclipse (1882), and the corona was much brighter at one limb than at the other in 1883. I think I can trace reversed Fraunhofer lines beyond the bright lines H and K away from the moon's edge."

It would seem probable that at the time of the eclipse of 1883 the amount of light-emitting gas was smaller relatively to the number of incandescent particles than at the time of the eclipse of the previous year. This supposition agrees with the fact that the scattered solar light, showing the Fraunhofer lines, was strong in 1883.

There may be another connection between the corona and the prominences besides that of a supply of gaseous matter—namely, one due to an increase of electric potential of the ejected matter when the prominences are numerous and large.

The electric disturbances which accompany the formation of large sun-spots are well known to be of sufficient magnitude to be felt upon the earth, by causing changes in the distribution of the terrestrial magnetism sufficiently great to affect our instruments.† The Astronomer Royal, writing of the

* *Phil. Trans.*, 1884, pp. 264 and 270.

† We do not know the mode in which the sun acts upon our magnets. The solar action may be a direct one due to changes in the sun's magnetism, or to an electro-magnetic action due to electric currents, or to electrified matter in motion with a high velocity. The views suggested in this lecture of the sun's electrified state and of the nature of the corona may possibly throw some light on this point. Two distinct modes of the sun's action on the magnetic needle seem to be possible:—

(a) The sun being a charged conductor separated from the earth by an insulating vacuum would affect the distribution of the earth's electricity by its power of statical induction. As the earth rotates currents would be set up about it to effect the redistribution of electricity required to satisfy the inducing influence of the sun. May we not find in these earth-currents an explanation of some of the phenomena of the earth's magnetism? However this may be, the changes in the sun's statical induction which would follow from the shooting forth of the electrified matter of the corona may well so affect the earth-currents as through them to bring about the disturbances observed in the needle. The electrified matter of the corona which leaves the sun will still go on, even when too diffused to be visible, and will still continue to produce upon the earth the effect due to its charge of electricity. (This view has been strengthened and greatly developed by our recently acquired know-

magnetic activity of the year 1882, says: "The month of November, which was characterised by the appearance of a very large sun-spot, being particularly disturbed with remarkable magnetic storms on November 17, 19, and 20, and many interesting cases of lesser disturbance." *

We can scarcely doubt but that similar electric disturbances of exceptional magnitude accompany the formation of the prominences; indeed these phenomena may themselves be, in part at least, electric discharges analogous to terrestrial aurorae.† However this may be, we can scarcely doubt that large electric disturbances accompany them. Tacchini takes the view that electricity plays a chief part in the prominences, and believes that he is able to show a connection between these phenomena and corresponding changes in the magnetism of our globe.‡

Hitherto in our discussion of the forces which may be active in the corona, we have taken account only of the influence of electrical changes which take place upon the sun. Now if these changes at the sun make themselves felt upon the earth, we may well suppose, with a high degree of proba-

ledge of electrons. 1909.) The amount of this action will depend greatly upon the direction of the projected matter relatively to the position of the earth.

(b) The other possible mode of action of the corona would be to suppose an electro-magnetic action upon the earth. The electrified coronal matter moving with a high velocity would act similarly in this respect to electric currents. (The magnetic action of such rapidly moving electrified solar matter over sun-spots has been quite recently the subject of special research by Hale. 1909.) Among other difficulties we must consider the rapid decrease of electro-magnetic action at a distance. (From this cause it has been shown by Larmor, and by Kelvin, that the view of a *direct* electric or magnetic influence from the sun upon the earth's magnets cannot be entertained. 1909.)

If the sun is a charged body, then in consequence of continually parting with matter charged with electricity of the same name as that of the sun's charge, the sun's potential would be slowly decreasing. This consideration would be in support of the conjecture thrown out in the last sentences of the text, that the corona was formerly of larger extent and that it will continue to diminish.—August 20, 1885.

[My attention has been called this day to a paper by Professor O. Reynolds, "On the Electro-dynamic Effect which the Induction of Statical Electricity causes in a Moving Body. This Induction on the part of the Sun a probable Cause of Terrestrial Magnetism." *Mem. Lit. and Phil. Soc., Manchester*, vol. v., 3rd Ser. p. 209.—Sept. 29, 1885.]

* "Report of the Astronomer Royal, 1883," p. 13.

† See Balfour Stewart, *Proc. Roy. Inst.*, vol. iv., p. 60.

‡ *Real Accademia dei Lincei* (March 1, 1885), vol. i., p. 181. Tacchini says: "Ciò viene anche a corroborare l'opinione mia e di qualche altri, che cioè nel fenomeno delle protuberanze solari l'elettricità attua una parte rilevante, da dovere forse considerare non poche di esse come fenomeni puramente elettrici, come aurore polari, capaci di indurre sul nostro globo i correspondenti disturbi magnetici; . . . noi possiamo intanto considerare come cosa assicurata alla scienza, che il fenomeno delle macchie solari, quelle delle protuberanze ed il magnetismo terrestre variano così di accordo."

At the same sitting Professor Respighi took a different view (p. 174), and stated he did not consider the prominences to be of a nature to occur in periods, and that he could not admit a connection between the maxima and minima of the prominences and the elements of terrestrial magnetism. At the following sitting, March 15 (p. 228), Tacchini replies to the objections of Respighi, and endeavours to show that Respighi has been influenced by his preconceived views of the nature of spots and prominences.

bility, that the earth,* and especially the nearer planets Venus and Mercury, exert an influence on the electrified and attenuated matter of the corona.

The elaborate researches of Mr. De la Rue and Professor Balfour Stewart appear to show an influence exerted by Venus and Mercury upon the solar regions of spot action.

We know nothing of the electric distribution on Venus and on Mercury, but it seems more than probable that these bodies, as well as the meteor-swarms nearer to the sun, have an influence in determining the mode of outflow of the electrified coronal matter in the directions in which they happen to be. The influence may be one of attraction, giving rise to coronal extension or rays from the corona, or to repulsion, in which case we might have what appears to us as a rift directed towards the body.

We have not sufficient data to furnish certain information on this point, but it may be of interest to quote the following sentences from Mr. Trouvelot's Report of the Eclipse of 1878 †:—

"There is a fact connected with this eclipse, which, if not due to a singular coincidence, would seem to point to some attractive action of the planets on the solar atmosphere (corona). On the day of the eclipse Mercury and Venus were in almost opposite points of their orbits, with the sun between and almost on a line with them, while the Earth on the same day was in a part of its orbit which formed the apex of an equilateral triangle having for base the line joining Mercury and Venus. Knowing this, it is perhaps singular, and anyhow very remarkable, to see that the eastern wing of the corona was directed on a straight line to Mercury, while the western appendage was directed on a straight line to Venus. The coincidence was still greater. As in regard to the sun, the two planets were not exactly on the same line, Mercury being a little to the north, while Venus was a little to the south of the ecliptic; the solar appendages have shown the same peculiarity, their axes being a little inclined to each other."

I may say that the inclination of the axes of coronal extensions on the two sides of the sun may be seen in the photographs of this eclipse. It should be stated that Professor Newcomb, who observed the coronal extension towards Venus, says: "I tried to judge whether the western one (ray) pointed towards the planet Venus, then plainly visible near the horizon. The direction was apparently very slightly below that of the planet." Professor Newcomb's words seem to show that he did not make any allowance for refraction, which

* Dr. Broun, in his discussion of the variations of the earth's magnetism (*Proc. Roy. Soc.*, vol. xxiv., p. 231), says: "It is shown that those changes (in 1844 and 1845) occur at intervals of twenty-six days, or multiples of twenty-six days. . . . As this period is that of the sun's rotation relatively to the earth, it appears to follow that the earth has some action on the sun, or (more probably) on some ray-like emanation from the sun, which causes these changes in the earth's magnetism."

† P. 93.

would make the planet when near the horizon appear sensibly higher than its true place.

If sufficient evidence should be forthcoming in the future to establish a sensible influence of the planets upon the corona we should not expect to see the coronal matter in all cases moving exactly towards or from a planet, because this matter would be also under the influence of a motion in the direction of its primary repulsion, and also of one of rotation about the sun.*

There has been some difference of opinion as to whether the corona is uniform in constitution from the sun's limb outwards, or whether it consists of two parts, which have been distinguished by the names "inner corona" and "outer corona."

There can be no doubt that at certain times, and in certain solar latitudes, a lower part of the corona, such as that described by Professor Langley, extending from about 5' to 10', is so much brighter than the parts outside of it that it seems to form what may be called an inner corona. At the same time, the photographs of different eclipses, and Mr. Wesley's drawings from some of them, show distinctly that all the stronger indications of structure can be traced down almost to the sun's limb, and that the brighter parts within some 6' to 10' of the limb are not equally bright all round the sun. This brighter inner part is represented very strongly in several drawings which accompany Mr. Stone's paper on the eclipse of 1874, especially in one by Mr. Wright.† There seems great probability that the corona is of the same nature throughout, but that there is often so much more matter—in other words, the coronal fog

* General Tennant, F.R.S., informs me that since this lecture was read, he has calculated the places of Mercury, Venus, and Mars for the eclipse of 1871 and the eclipse of 1882. He says:

"The positions at the eclipse of 1871 are—

Mercury position angle	$100^{\circ} 39'$
Venus	$278^{\circ} 40'$
Mars	$80^{\circ} 40'$

Mercury is thus not far from the direction of the great prominences lettered H and I (see catalogue at page 27 of my report, *Mem. R.A.S.*, vol. xlii.), and corresponds to the greatest extension of the coronal matter, namely, 45' in my table. Venus is near the group lettered V, W, and X, of which group V is less only to H and I in height, and corresponds to the next greatest extension of the corona, namely, 34' 56" in my table. The real heights of the visible extensions, allowing for the foreshortening, would be for Mercury 41' 3" or 45' 31", according to the reading taken; and for Venus 47' 05". Any such calculation, however, implies a form of the coronal extension which does not exist. The more foreshortened ray would, in fact, on account of its breadth, seem longer in proportion than the one which is seen more nearly perpendicularly to its axial direction; and in this case this consideration would tend to reduce the real extension of the Venus ray. Mars does not seem to have any marked ray directed to him, but any such ray would be much foreshortened if it existed.

"At the time of the eclipse of May 16, 1882 (*Phil. Trans.*, vol. clxxv., Plate 13), we should have the effects of the planets Mercury and Venus coincident, and not much foreshortened, in the coronal pictures. The combined effects of these planets are shown in the protruding angle at the upper left side of the engraved corona. There seems a marked protrusion of the general light thereabouts which would be opposite to the planets."—August 15, 1885.

† *Mem. Roy. Astron. Soc.*, vol. xlii., pp. 43, 51, and 53.

is so much denser—within 5' to 10' of the limb, that under the effects of projection, and when seen by the eye or with a very low power, this part of the corona appears to be marked off from the corona beyond. It is possible that a clue to the real state of things may be found in the photographs of the corona of 178. When these are examined the long equatorial rays seen by the eye can be traced a little distance beyond the bright corona; but it is found that the corona, as a whole, is not drawn out at this part so as to extend to several solar diameters, but that these great extensions consist of rays or streamers coming out from the general coronal mass, something in the way in which fainter rays often extend from the principal tail of a comet. They may be due to a similar cause, namely, the electric repulsion acting upon particles which are more completely under its sway, either from their less specific gravity or their more highly electrified condition. The consideration presents itself whether, in this state of things, we have only an extreme case of the conditions always present in the corona, which gives rise to the appearances which have suggested the distinction of an "inner corona" and an "outer corona."

There is another question which awaits consideration—namely, whether the corona rotates with the sun. It seems obvious that if the corona is due to a supply of matter and to forces coming from the sun, then the coronal structure and the degree of extension, which are produced by them, at any part of the sun, would continue to be produced by these agencies at that part of the sun, and in that sense the corona would rotate. In the case of the more distant and diffused parts the rotation could scarcely be of one and the same material object any more than in the sweep of a comet's tail at perihelion, the corona being constantly renewed and re-formed over each part of the solar surface. If we suppose the corona to come under the influence of an external force as that of a planet, then we should expect the ray drawn out towards it, or the rift formed opposite to it, to continue to be directed to this external object, and to be independent of the solar rotation. The subpermanence of any great coronal form, therefore, would probably have to be explained by the maintenance for some time of the conditions upon which the form depends, and not by an unaltered identity of the coronal matter; as in the case of a cloud over a mountain top, or of a flame over the mouth of a volcano.

We have to consider another question: What becomes of the coronal particles? Are they carried away from the sun, as the matter of the tails of comets is lost to them; or do they return to the sun?

The results of eye-observations, as well as of the taking of photographs with different exposures, have shown that there is great probability that the corona has not an outer boundary, but that it is lost in an increasing faintness and diffusion. The absence of a limit is probably true only of the faint

outer parts of the corona. Within, and especially about the distance from the sun's limb to which the so-called "inner corona" usually extends, there is evidence of an apparent arrest of coronal matter, due in part probably to the effects of perspective, and within this distance are seen numerous rays which turn round and descend towards the sun. These returning curved forms are well shown in Mr. Wesley's drawings of the eclipse of 1871.*

We are led to the conclusion that many of the coronal particles return to the sun, but that in the case of other particles, which form the stronger coronal rays and streamers, there is no return, but that they leave the sun, and, at the same time, separate more widely from each other by their mutual repulsion, and become too diffused to be visible. The state of extreme attenuation of this diffused coronal matter—such that the nuclei of comets pass through it without sensible retardation—enables us to see that the corona may be maintained at an extremely small expenditure of solar material. Among other considerations it may be mentioned that an electric repulsion can maintain its sway only so long as the repelled particles remain in the same electrical state; if through electric discharges the particles cease to maintain the electric potential they possess, there will be no longer any force of repulsion acting upon them, and gravity will be no longer mastered. (We now know experimentally that there is the pressure of the sun's radiation, acting according to the minuteness of the particles, and also an outflow of electrons. 1909.) If when this takes place the particle is not moving away with a velocity sufficiently great to carry it from the sun, the particle will return to the sun. Of course, if the effect of any electric discharges or other local conditions has been to change the potential of the particle from positive to negative, or the reverse, as the case may be, then the repulsion would be changed into an attraction acting in the same direction as gravity.

This ceaseless outflow of extremely minute particles, very widely separated from each other, may possibly throw some light on another phenomenon which has not yet been satisfactorily explained—namely, the zodiacal light.

The views which I have ventured to put forward in this lecture would lead us to expect that a more extended and more brilliant corona surrounded the sun in early geological time, and that if the skies were then of their present degree of clearness, the corona would probably have been visible about the sun.

May the corona have been still faintly visible in the earliest ages of the human race? Are there any philological traces of it in the earliest words and ideas connected with the sun? On those eastern plains, where the air is of so great purity, did early men still see faintly a true *παρῆλιος*?

Similar considerations point to a slow secular diminution in extension and

* *Mem. Roy. Astron. Soc.*, vol. xli., Plates 6, 7, 8, and 10.

in brightness of the corona, as the sun slowly loses heat, and the actions of the photosphere become less fervent.

The candle of the sun is burning down, and so far as we can see, must at last reach the socket. Then will begin a total eclipse which will have no end :

“Dies illa
Solvet seclum in favilla.”

ON THE DUPLICITY OF THE SOLAR LINE D₃

(From *Astronom. Nachrichten*, No. 3302, p. 329, July 19, 1895)

As soon as Runge and Paschen announced that the yellow line of the gas from cleveite was double, I made some observations on the helium line in the sun, but at that time I failed to see the line double (*Chem. News*, No. 1855), owing probably, as I now believe, to the thin cloud present at the time. For with a bluer sky, we have since had no difficulty in seeing D₃ as a double line similar to the terrestrial pair photographed by Runge and Paschen.

In the chromosphere close to the limb both components are usually much expanded, and then the interval between them is very small, and can be seen only with some difficulty; but farther from the limb, and in prominences, the lines thin out, and form a pair of very fine lines, of which the less refrangible one is much fainter.

The pair of terrestrial lines near the helium lines on the less refrangible side furnish a convenient scale by which the separation of the bright lines may be estimated, and showed that the helium lines were about the same distance apart as the pair of yellow lines of the cleveite gas according to Runge and Paschen.

On one occasion, owing to the shift through motion in the line of sight of the expanded double helium line, a terrestrial line was seen upon it, as appears to have been the case in the observations of Belopolsky (*Mem. Soc. Spett. Ital.*, May 1894).

The observations were made in the spectra of the third and fourth orders of a grating having 14,438 lines to the inch. The lines were seen double on July 10, 11, and 13.

WILLIAM HUGGINS.

July 14, 1895.

A SUGGESTED EXPLANATION OF THE SOLAR CORONA

(From *Astrophys. Journ.*, vol. xii., p. 279, 1900)

PROFESSOR SCHEINER, in a paper bearing the above title (*Astrophys. Journ.*, vol. xii., p. 23), makes the statement: “. . . that the opinion seems to have

been general that this incandescence (of solid or liquid particles) arises in a manner similar to that of shooting stars and meteors from friction in the outer solar atmosphere" (p. 25).

And further on he says: "The idea that the cause of the incandescence of the meteoric particles in the neighbourhood of the sun is to be found in the direct solar radiation is so obvious that it is surprising that it has not hitherto been expressed in the literature of the subject—at least, I have not been able to find anything of the sort" (p. 26).

For the sake of historical accuracy it seems to me to be desirable to point out that in my Bakerian Lecture on the Corona of the Sun, given before the Royal Society in 1885, the view taken of the corona was inconsistent with the meteoric friction hypothesis, and, indeed, the incandescence of the solid or liquid particles was attributed directly to the "enormous radiation" of the sun to which they were subjected. I will confine myself to two or three short extracts.

"These considerations appear to me to be of great weight in support of the view that, though some meteoroid and some cometary matter may fall into the sun, the corona consists essentially of matter coming from the sun . . . the corona must therefore consist of a fog in which the particles are incandescent and in which the gaseous matter does not form a continuous atmosphere . . . a fog even so extremely attenuated would probably be fully sufficient to give rise to the corona under the enormous radiation to which it is subjected."

The main conclusions at which I had arrived in 1885 were summed up in my Presidential Address of 1891 (*Report Brit. Assoc.*, 1891, p. 1) in the following words :

"In a discussion in the Bakerian Lecture for 1885, of what we knew up to that time of the sun's corona, I was led to the conclusion that the corona is essentially a phenomenon similar in the cause of its formation to the tails of comets—that it consists for the most part probably of matter going from the sun under the action of a force, possibly electrical,* which varies at the surface, and can therefore in the case of highly attenuated matter easily master the force of gravity even near the sun. Though many of the coronal particles may return to the sun, those which form the long rays or streamers do not return; they separate and soon become too diffused to be any longer visible, and may well go to furnish the matter of the zodiacal light, which otherwise has not received a satisfactory explanation" (*loc. cit.*, p. 11).

Sept. 26, 1900.

* Maxwell's pressure of radiation had not then been experimentally established. (1909.)

Section VIII
MOON, PLANETS, AND AURORA

LIST OF PAPERS

"Note accompanying Drawings of Jupiter and Mars."

Monthly Notices R.A.S., vol. xvii., p. 23. 1856. P. 359.

"Observations of the Occultation of Jupiter, 1856."

Monthly Notices, vol. xvii., p. 2.

"On the Occultation of α Virginis, 1857."

Monthly Notices, vol. xvii., p. 246.

"Observations of the Spectra of the Moon and Planets." (And Dr. Miller.)

Phil. Trans., vol. cliv., pp. 413-435. 1864. P. 359.

"On the Occultation of ϵ Piscium, Jan. 4, 1865."

Monthly Notices, vol. xxv., p. 60.

"On the Spectrum of Mars, with some Remarks on the Colour of that Planet."

Monthly Notices, vol. xxvii., p. 178. 1867. P. 369.

"On the Lunar Crater Linné."

Monthly Notices, vol. xxvii., p. 296. 1867. P. 372.

"On the Appearance of Mercury at its Transit, Nov. 5, 1868."

Monthly Notices, vol. xxix., p. 25. 1869.

"On the Spectrum of Uranus, and of Comet I, 1871."

Proc. Roy. Soc., vol. xix., p. 488. P. 375.

"Photographic Spectra of Moon and Planets."

Phil. Trans., 1880, Part II., p. 669. P. 377.

"Sur le Spectre photographique d'Uranus."

Comptes rendus, 1889, p. 1228.

"On the Photographic Spectra of Uranus and Saturn." (And Mrs.

Huggins.)

Proc. Roy. Soc., vol. xlvi., p. 231. 1889. P. 378.

"On the Atmospheric Bands in the Spectrum of Mars, 1895." (And

Mrs. Huggins.)

Astrophys. Journ., vol. i., p. 193. 1895. P. 380.

"Photographic Spectra of the Planets."

Astrophys. Journ., vol. i., pp. 196 and 273. 1895. P. 381.

"On the Wave-length of the Principal Line in the Spectrum of the

Aurora."

Proc. Roy. Soc., vol. xlv., p. 430. 1889. P. 386.

NOTE ACCOMPANYING DRAWINGS OF JUPITER AND MARS

(From *Monthly Notices R.A.S.*, vol. xvii., p. 23. 1856)

I SEND herewith drawings of Jupiter for October 14 and 15. On each occasion the planet was watched for a considerable time, but no change of appearance or of relative position was observed except that due to Jupiter's rotation.

Also drawings of Mars for April 28 and May 19.

NOTE

(The drawings of Jupiter presented to the Royal Astronomical Society in 1856 were made with the 5-in. Dolland refractor.

The views of Jupiter in 1858–1860, reproduced on the accompanying plates, pp. 361, 363, were drawn with the fine 8-in. object-glass by Alvan Clark, which was mounted in the Observatory in January 1858.)

OBSERVATIONS ON THE MOON AND PLANETS

(From *Phil. Trans.*, vol. cliv., pp. 413–435. 1864)

IT is well known that in the solar spectrum many additional lines make their appearance when light from the sun seen near the horizon reaches the observer, after having traversed a much greater length of our atmosphere than when the sun is viewed at greater altitudes. This circumstance suggested to us the importance of a careful examination of the solar light after reflection from the moon and planets, in reference to the extent and analogous constitution of atmospheres possibly surrounding these bodies. As far as practicable, the spectra of the moon, Venus, Mars, Jupiter, and Saturn have been observed on several occasions with this special object in view.

The Moon.—All the astronomical phenomena in which we should expect

to discover indications of an atmosphere about the moon, if such exist, agree in showing the non-existence of a lunar atmosphere of sensible amount. From the absence of appreciable refraction at the moon's limb, and from the *sudden* extinction during a total eclipse of stars of even the tenth and eleventh magnitude at the limb of the moon, "we are," writes Sir John Herschel, "entitled to conclude that no amount of appreciable vapour is suspended near the surface of the moon, and . . . the non-existence of an atmosphere at the moon's edge having the 1980th part of the density of the earth's atmosphere."*

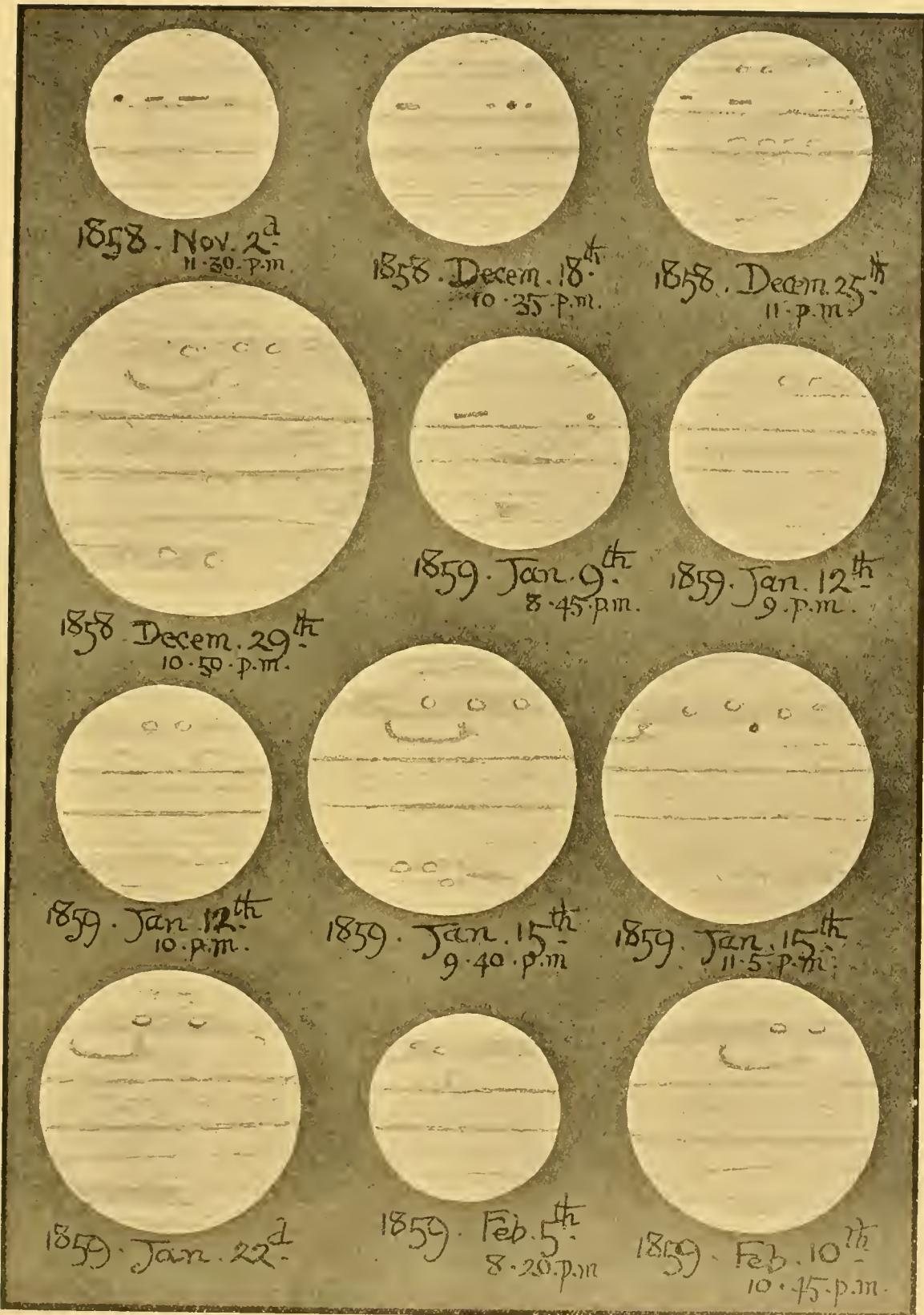
As by direct observation we know that the solar light is reflected from the *surface* of the moon, the light which reaches the earth after having undergone this reflection must have passed through a length of lunar atmosphere, if such exist, at least equal to double the height of such atmosphere above that surface of the moon which is visible to us. From some parts of the moon, when the whole or a large part of its illuminated surface is turned towards the earth, the length of the column of lunar atmosphere which the solar light would have to traverse would be considerably greater.

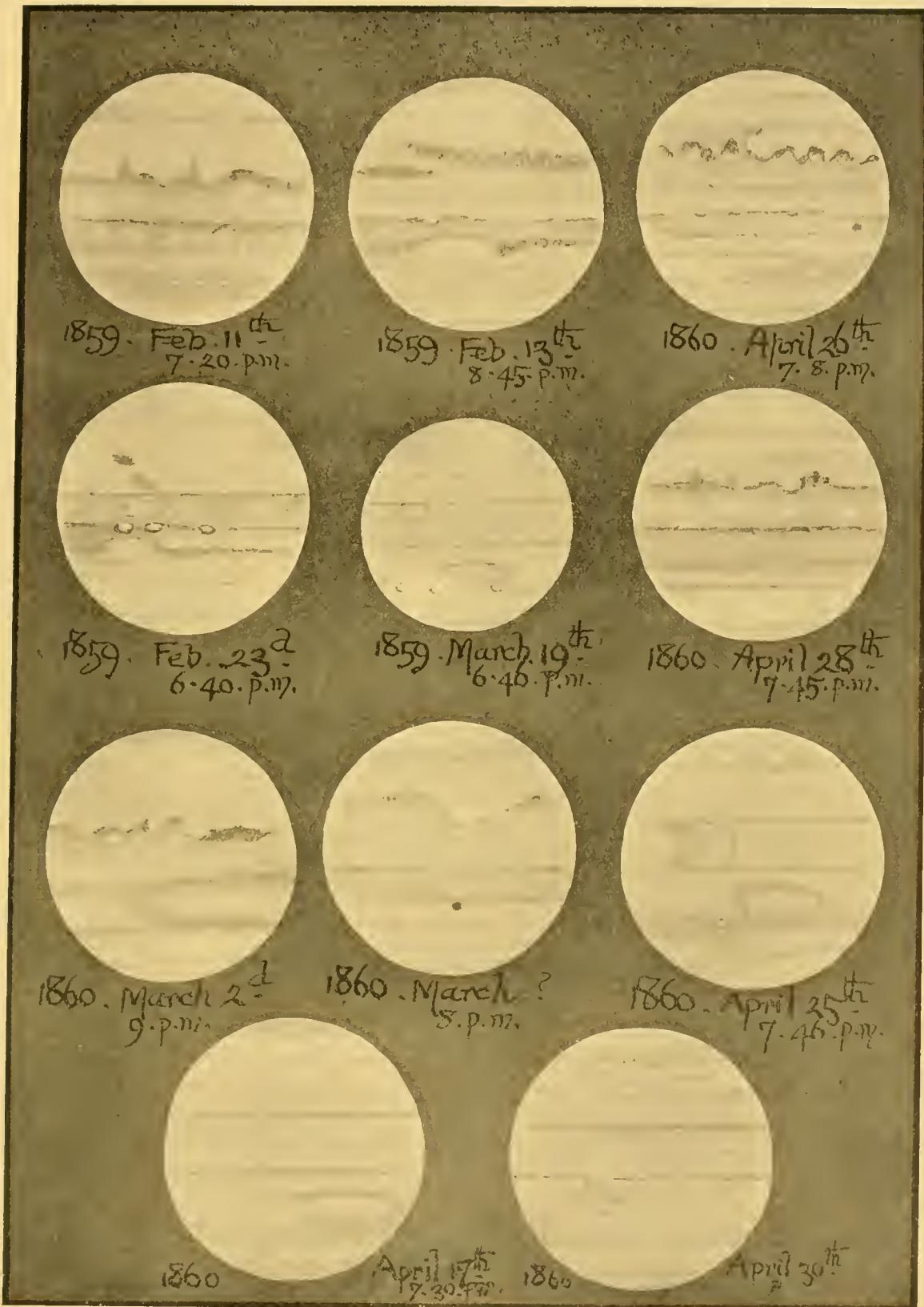
The examination of lunar light by the spectroscope, and the comparison of the light reflected from different portions of the moon's illuminated surface with each other by this method, would take place under conditions favourable to the detection of an atmosphere of considerable extent, if such exist.

The moon was examined by us on April 12 and November 26, 1862, March 31 and December 31, 1863, March 15 and 19, and April 12, 1864. The solar lines were perfectly well seen, appearing exceedingly sharp and fine. The line D was well divided, and its components were observed to coincide with those of sodium. Coincidence of the magnesium group with the three lines forming δ was also observed. The lunar spectrum is indeed full of fine lines, and they were well seen from B to about halfway between G and H. On all these occasions no other strong lines were observed than those which are visible in the solar spectrum when the sun has a considerable altitude.

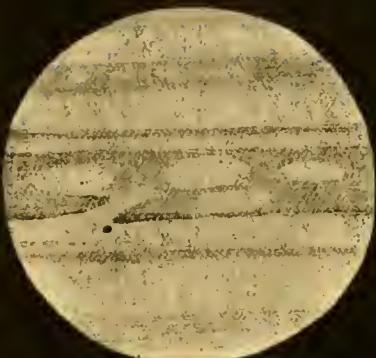
Previously to the observations of March 15 and 19 and April 12, 1864, the apparatus was directed to the sun when near the horizon, and the relative positions and characteristic appearances of the atmospheric lines in the orange and red were carefully observed. These portions of the spectrum were closely scrutinised when the moon's light was afterwards examined; but no indication of similar lines could be detected. On each of the three evenings just mentioned successive portions of the moon's illuminated surface from the centre to the circumference were brought before the slit of the spectrum apparatus. The quantity of light from different parts was observed to be very different, but

* "Outlines of Astronomy," 7th ed., par. 431, p. 284. See also a paper by Professor Challis in the *Monthly Notices R.A.S.*, vol. xxiii, p. 254, June 1863.

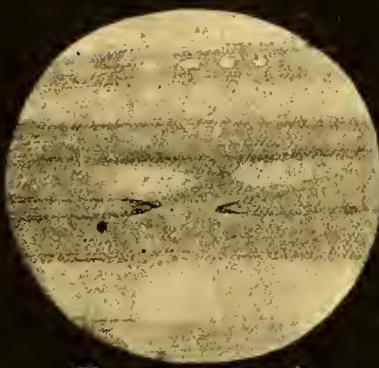




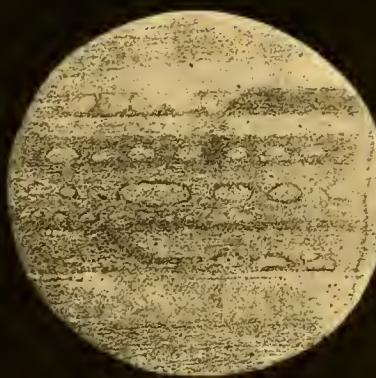
JUPITER



1873 - March 24



1873 - March 26
9 p.m.



1873 - April 23
8-20 p.m.

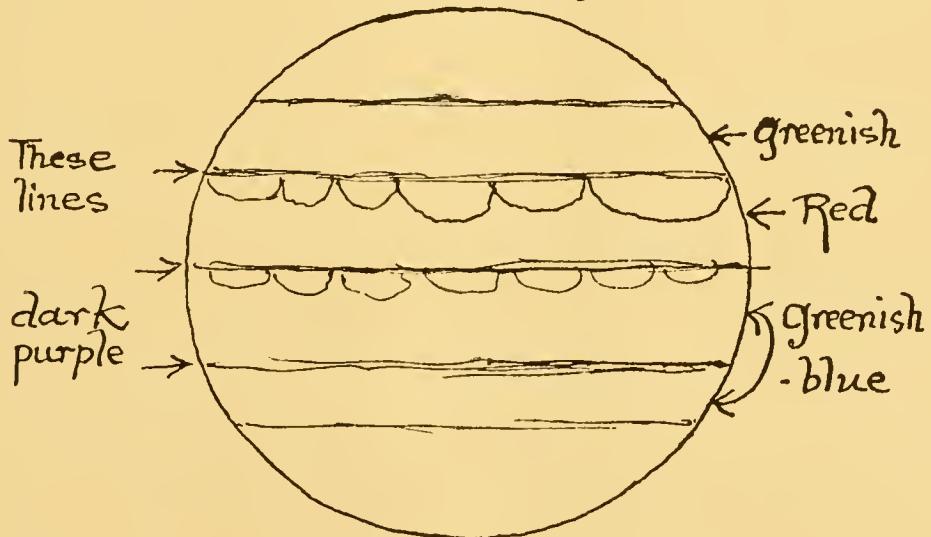
Notes on Drawings of Jupiter.

The three drawings of Jupiter, of 1873 and the diagram which follows were made with the object-glass by Sir Howard Grubb of 15 inches aperture and 15 feet focal length.

Of the drawing of March 26th it is noted; - "upper part of broad middle belt, reddish-brown; 4th satellite quite black-looking; might be taken for a shadow."

On May 12th, it is recorded that in the spaces between the larger ovals there were one to three small ovals.

1872 · Jan. 13.



This diagrammatic drawing is carefully copied from the Observatory Book, for the colour notes. There is a note saying that the colours were marked; that the red appeared vermillion.

not the smallest change in the lines of the spectrum could be perceived, either in respect of relative intensity or the addition or disappearance of any lines.*

The result of this spectrum analysis of the light reflected by the moon is wholly negative as to the existence of any considerable lunar atmosphere.†

The Planets Venus, Mars, Jupiter, and Saturn.—The very sensible and rapidly changing appearances of the disk of Jupiter, other than those due to the rotation of the planet, present very strong evidence of the existence of a very considerable atmosphere about Jupiter. The same, though in a much less marked degree, is probably true of Saturn and Mars. In addition, the diminished brightness of the disk of Jupiter near the periphery supports the inference that an atmosphere exists about that planet.

The planet Jupiter was observed on April 12, 1862, and April 14 and May 1, 1863. The solar lines B, C, D, E, *b*, F, and G were seen, with numerous fine intermediate lines, and D, E, *b*, and F were measured; but no marked lines other than those usually present in the solar spectrum were detected.

[Since these observations were made, we have had a spectrum apparatus constructed by Mr. Browning, optician, of the Minories, which is similar in general arrangement to that already described, but possesses much less dispersive power. In this apparatus the cylindrical lens, the collimating lens, and the object-glass of the small telescope correspond exactly in diameter and in focal length with those of which a description has been given; but the eyepiece of the telescope is of less power, and has a magnifying power of about three diameters. A second eyepiece was occasionally used, magnifying nine diameters. Two prisms are employed; one has a refracting angle of 35° , the other a refracting angle of 45° .

* [With the spectrum apparatus described at p. 10, the spectra of particular and very limited regions of the moon's surface can be examined. The opening of the slit of the apparatus corresponding to a spectrum that can be separately observed is about $\frac{1}{300}$ inch $\times \frac{1}{100}$ inch. The image of the moon formed by the object-glass of the telescope has a diameter of 1.04 inch. Practically it is found that the light reflected from an area upon the surface of the moon of about one-third that of Tycho can be analysed in the instrument.]

The particular spot of the moon's surface under observation can be ascertained by means of the finder attached to the telescope. For this purpose, however, a special set of wires, accurately adjusted, and an eyepiece of considerable power are necessary. When the part of the moon's surface under observation presents marked inequalities of illumination, the spectra of these differently illuminated portions can be easily recognised by the differences in their comparative brightness. In these observations the cylindrical lens may be removed.—August 31, 1864.]

† [A remarkably favourable opportunity of observing the effect upon the solar spectrum of transmission through a very large extent of the earth's atmosphere presents itself on the occasion of an eclipse of the moon. We had made preparations to observe the copper-coloured light reflected from the moon during the eclipse of June 1, 1863. The small altitude of the moon on this occasion rendered the observation impossible, from the circumstance that the eye end of the telescope, increased in length by the spectrum apparatus, came too near the wall of the observatory.—August 31, 1864.]

With this apparatus, in the spectrum of Jupiter a strong line in the red is seen which is scarcely distinguishable with the more powerful instrument, and was from this cause overlooked in our earlier observations. The remarkable increase of visibility of this line is due to the much greater brilliancy of the spectrum in this apparatus; and this is much more than inversely proportional to the diminution of the dispersion, since, on account of the greatly reduced obliquity of incidence, the loss of light at the surfaces of the prisms by reflection is much less. This saving of light in the spectrum apparatus is of very great importance in observations of the planetary spectra. The image of a planet in the telescope is not a point, but forms a disk of considerable magnitude relatively to the image of a star. Of this image, enlarged in one direction by the cylindrical lens, a very narrow section only, corresponding to the breadth of the slit, passes on through the collimating lens to the prisms; and this portion only of the total light collected by the object-glass becomes available to form the spectrum. On this account we have found the observations of the planets much more difficult than would be observations of stars possessing an equal apparent brilliancy.

This band of which we are now speaking in the spectrum of Jupiter occurs in a rather obscure part of the spectrum; moreover, by the instrument of greater dispersive power, it appears to be resolved into two or more lines, which are severally very faint, and are less visible than a single stronger line. The altitude of Jupiter being small (about 22° above the horizon) at the time of observation, it was of great importance to have satisfactory evidence that this band was not due to absorption by our atmosphere.

On June 16, 1864, the moon and Jupiter being near each other in the sky, the opportunity was seized to compare directly the moon's light with that of Jupiter under precisely similar conditions of atmosphere. The observations of this evening were decisive in showing that this band in the spectrum of Jupiter was due to a modification suffered by the solar light before reaching our atmosphere, and therefore due probably to absorption by the atmosphere of Jupiter.

On June 20, and on July 12 and 14, an observation still more crucial was obtained. The length of the opening of the slit is much greater than the diameter of the telescopic image of Jupiter, even after elongation by the cylindrical lens. If, therefore, at the time of observation the light from the sky is sufficiently intense to form a visible spectrum, the spectrum of the sky is seen in the instrument together with the spectrum of Jupiter, and much exceeding it in breadth. When the period is so chosen that the degree of illumination of the sky is suitable in proportion to the intensity of the light of Jupiter, the solar lines and those due to our atmosphere are well seen in close contiguity with the lines in the spectrum of Jupiter, and occupying exactly similar relative

positions. The sky-spectrum is seen under precisely similar conditions of altitude and of state of atmosphere. To the light of Jupiter under these circumstances of observation is added the light reflected from the small area of sky immediately between the observer and the planet. This light is, however, too faint in proportion to that of Jupiter to become a source of error. In the diagram, fig. 3, p. 9, the position of this band is shown relatively to the spectrum of the sky. The band at 914 of the scale appears to be coincident with, but *much stronger* than, a faint band in the sky-spectrum. This increase in the strength of the band is probably due to an absorptive action exerted by the atmosphere of the planet.

The bands at 882 and 1033 of the scale are less intense in the spectrum of Jupiter than in the spectrum of the light of the sky. This variation of intensity is probably due to the circumstance that the light from the southern sky, before it is reflected to the observer, on account of the position of the sun, which is then near the horizon, has had to traverse a very much larger amount, and a more dense portion, of our atmosphere than that traversed by the light received from Jupiter. It is in accordance with this explanation that these bands are also less intense in the spectrum of the moon when similarly compared with those of the sky.

Other lines less refrangible were perceived in the spectrum of Jupiter, but were not sufficiently distinct to be measured. The bands in the orange and the red to which we have referred, when examined in the spectrum apparatus of greater dispersive power, and with a much stronger illumination by directing the apparatus to the sun when near the horizon, are resolved into groups of lines. The stronger of these lines are represented in the upper spectrum of the diagram. The relative position of the band in the red due to lines of oxygen and nitrogen when the induction spark is taken in air, is shown below the spectrum of Jupiter. This band is in a small degree more refrangible than the strong band due to Jupiter.

If this band, at 914 of the scale, in Jupiter's spectrum consists of lines severally coincident with the lines composing the faint atmospheric band with which it appears to correspond in position, it would seem entitled to be regarded as an evidence of the similarity of Jupiter's atmosphere with our own, with respect at least to one of its constituents, or to one of the vapours diffused through it. The smaller intensity of the bands 882 and 1033 would appear to oppose the supposition that Jupiter's atmosphere is identical with our own. This negative evidence, however, cannot be regarded as of much weight, since telescopic observations show that the light which we receive from Jupiter is for the most part reflected from clouds floating in its atmosphere at an elevation above the planetary surface. The solar light, therefore, would not traverse the lower and denser portions of Jupiter's atmosphere, corresponding to those

of our own atmosphere in which the vapours, which probably produce these lines, appear to be chiefly present. The band about C, and that a little more refrangible at 838 of the scale, appear quite as strong in Jupiter as in the light from the sky. It may therefore be supposed that these bands are in part due to absorption at Jupiter, since the light from Jupiter suffers less absorption from our atmosphere than does the solar light reflected from the sky under the circumstances in which the observations were made.

With the exception of these bands in the orange and the red, the spectrum of Jupiter appeared to correspond exactly with that of the sky.—August 31, 1864.]

Saturn was observed on April 12, 1862, April 14, 1863, and April 12, 1864. Several solar lines were seen, but the spectrum was too faint to permit of any satisfactory determination as to the presence or absence of atmospheric lines.

[The spectrum of Saturn was observed with the apparatus, and in the manner described when speaking of Jupiter, on June 13, 16, and 20. The spectrum was more difficult of observation, on account of the feebler brilliancy of Saturn, and its less favourable position. Bands in the red and orange were seen similar to those in the spectrum of Jupiter, and by measurement these bands were found to occupy positions in the spectrum corresponding to those of the bands of Jupiter.—August 31, 1864.]

The spectrum of Mars was observed on November 6, 1862, and April 17, 1863. The principal solar lines were seen, and no other strong lines were noticed.

[On August 10 and 29, 1864, we re-examined Mars, using the new spectrum apparatus. No lines in the red, similar to those of Jupiter and Saturn, were observed; but in the extreme red, probably about B and α , two or three strong lines were seen. With the exception of these, no lines were detected in the red, orange, yellow, and green portions of the spectrum, other than those of the solar spectrum. At about F the brilliancy of the spectrum diminishes in a remarkable manner, in consequence of a series of strong and nearly equidistant bands, which commences at F and continues towards the more refrangible end as far as the spectrum can be traced. The absorption of these bands is evidently the cause of the predominance of the red rays in the light of this planet.*

The spectrum apparatus of greater power resolves these bands in the blue into groups of lines.—August 31, 1864.]

The light of Venus gives a spectrum of great beauty. The observations were chiefly made on April 17, 22, and 26, 1863. The line D was seen double. B, C, and numerous solar lines to a little distance beyond G, were distinctly

* See p. 370.

visible; and the principal of these were measured and found to agree with corresponding lines in the solar spectrum. Lines other than these, and in the position in which the stronger atmospheric lines present themselves, were carefully looked for, but no satisfactory evidence of any such lines has been obtained. Venus was observed as early in the evening as possible, and while a considerable amount of daylight still remained.

The imperfect evidence which analysis by the prism affords of the existence of atmospheres around these planets, notwithstanding the high probability, amounting almost to certainty in the case of Jupiter, that such atmospheres do exist, may receive an explanation in the supposition that the light is chiefly reflected, not from the planetary surfaces, but from masses of cloud in the upper strata of their atmospheres. In this case the length of atmosphere which the light would have to traverse would be considerably lessened. With perhaps the exception of Mars, telescopic observations are in favour of such a supposition.

ON THE SPECTRUM OF MARS, WITH SOME REMARKS ON THE COLOUR OF THE PLANET

(From *Monthly Notices R.A.S.*, vol. xxvii., p. 178, 1861)

ON several occasions during the late opposition of Mars, I made observations of the spectrum of the solar light reflected from the planet.

The spectroscope which I employed was the same as that of which a description has appeared in my former papers.* Two instruments were used, one of which is furnished with a single prism of dense glass, which has a refracting angle of 60. The other instrument has two similar prisms.

In a paper, "On the Spectra of some of the Fixed Stars," † by myself and Dr. Miller, we state that on one occasion several strong lines of absorption were seen in the more refrangible parts of the spectrum of Mars.

During the recent more favourable opportunities of viewing Mars, I again saw lines in the blue and indigo parts of the spectrum. However, the faintness of this portion of the spectrum, when the slit was made sufficiently narrow for the distinct observation of the Fraunhofer lines, did not permit me to measure with accuracy the positions of the lines which I saw. For this reason I was unable to determine whether these lines are those which occur in this part of the solar spectrum, or whether any of them are new lines due to an absorption which the light suffers by reflection from the planet.

I have confirmed our former observation that several strong lines occur in the red portion of the spectrum. Fraunhofer's C was distinctly seen, and

* *Phil. Trans.*, 1864, p. 485.

† *Ibid.*, vol. cliv., pp. 413-435.

its identity determined by satisfactory measures with the micrometer of the spectrum apparatus. From this line the spectrum, as far as it can be traced towards the less refrangible end, is crossed by dark lines. One strong line was determined by the micrometer to be situated from C, at about one-fourth of the distance of C to B. As a similar line is not found in this position in the solar spectrum, the line in the spectrum of Mars may be accepted as an indication of absorption by the planet, and probably by the atmosphere which surrounds it. The others in the red may be identical, at least in part, with B and α , and the adjacent lines of the solar spectrum.

On February 14, faint lines were seen on both sides of Fraunhofer's D. The lines on the more refrangible side of D were stronger than the less refrangible lines. These lines occupy positions in the spectrum apparently coincident with groups of lines which make their appearance when the sun's light traverses the lower strata of the atmosphere, and which are therefore supposed to be produced by the absorption of gases or vapours existing in our atmosphere. The lines in the spectrum of Mars probably indicate the existence of similar matter in the planet's atmosphere. I suspected that these lines were most distinct in the light from the margins of the planet's disk, but this observation was, to some extent, uncertain. That these lines were not produced by the portion of the earth's atmosphere through which the light of Mars had passed, was shown by the absence of similar lines of equal strength in the spectrum of the moon, which at the time of observation had a smaller altitude than Mars.

I observed also the spectra of the darker portions of the planet's disk. The spectrum of the dark zone beneath the Southern Polar spot appeared as a dusky band when compared with the spectra of the adjoining brighter parts of the planet. This fainter spectrum appeared to possess a uniform depth of shade throughout its length. This observation would indicate that the material which forms the darker parts of the planet's surface absorbs all the rays of the spectrum equally. These portions should, therefore, be neutral, or nearly so, in colour. I do not now regard the ruddy colour of Mars as the result of an elective absorption—that is, an absorption of certain rays only so as to produce dark lines in the spectrum.

Further, it does not appear to be probable that the ruddy colour which distinguishes Mars has its origin in the planet's atmosphere, for the light from the polar regions is free from colour, though this light has traversed a longer column of atmosphere than the light from the central parts of the disk. It is in the central parts of the disk that the colour is most marked. If, indeed, the colour is produced by the planet's atmosphere, it must be referred to peculiar conditions of it which exist only in connection with

particular portions of the planet's surface. The evidence which we possess at present appears to support the opinion that the planet's distinctive colour has its origin in the material of which some parts of the surface are composed. Mr. Lockyer's observation that the colour is most intense when the planet's atmosphere is free from clouds, obviously admits of an interpretation in accordance with this view.

The opinion appears to receive support from the photometric observations of Seidel and Zöllner, some of the results which I will briefly state. These observations show that Mars resembles the moon in the anomalous amount of variation of the light reflected from it, as it increases and decreases in phase; also in the greater brilliancy of the marginal portions of the disk. Further, Zöllner has found that the albedo of Mars, that is, the mean reflective power of the different parts of the disk, is not more than about one-half more than that of the lunar surface. Now these optical facts are in accordance with telescopic observation that in the case of Mars the light is almost wholly reflected from the true surface of the planet. Jupiter and Saturn, the light from which has evidently come from an envelope of clouds, are, on the contrary, less bright at the margin than at the central part of the disk. These planets have an albedo severally, about four and three times greater than that of the moon.*

The anomalous degradation in brightness of the moon at the phases on either side of the full, as well as the greater brilliancy of the limb, may be accounted for by the supposition of inequalities on its surface, and also by partly regular reflective property of its superficial rocks. Zöllner has shown that if these phenomena be assumed empirically to be due to inequalities, then the angle of mean elevation of these inequalities must be taken at 52° . On the same hypothesis the more rapid changes of Mars would require an angle of 76° .†

It appears to be highly probable that the conditions of surface which give rise to these phenomena are common to the moon and to Mars. The considerations referred to in a former paragraph suggest that these superficial conditions represent peculiarities which exist at the true surface of the planet. In this connection it is of importance to remark that the darker parts of the disk of Mars gradually disappear, and that the coloured portions lose their distinctive ruddy tint as they approach the limb.

The observations of Sir John Herschel‡ and Professor G. Bond § give a mean reflective power to the moon's surface, similar to that of a "grey,

* "Photom. Untersuchungen von Dr. J. Zöllner," Leipzig, 1865.

† *Ibid.*, p. 113.

‡ "Outlines of Astronomy," p. 272.

§ *Mem. Amer. Academy*, vol. viii., p. 222.

weathered sandstone rock." Zöllner has confirmed this statement. According to him :

The albedo of the Moon	= .1736 of the incident light
" " Mars	= .2672 " "
" " Jupiter	= .6238 " "
" " Saturn	= .4981 " "
" " White paper	= .700 " "
" " White sandstone	= .237 " "

From this table it appears that Mars takes in for its own use .7328 of the energy which it receives as light. Jupiter's cloudy atmosphere, nearly as brilliant as white paper, rejects more than six-tenths of the light which falls upon it; therefore less than four-tenths of the light which this distant planet receives is alone available for the purposes of its economy.

The photographic researches of Mr. De la Rue and others show that the lights of high refrangibility, which are specially powerful in producing chemical action, are similarly affected.*

At present we know nothing of the reflective power of the planets for those rays of slower vibration which we call heat.

NOTE ON THE LUNAR CRATER LINNÉ

(From *Monthly Notices R.A.S.*, vol. xxvii., p. 296, 1867)

THE diagram which accompanies this note represents the Crater *Linné* as it appeared in the telescope on May 11, 1867. The unusual steadiness of the atmosphere permitted the small crater upon *Linné* to be seen with great distinctness.

Linné on this occasion presented the appearance of an oval white patch on the darker background of the *Mare Serenitatis*. The character of the surface of the white spot may be described as similar in appearance to that of a cloud, for it presented no distinct details, and remained undefined when the small neighbouring craters were seen with great clearness. The absence of any defined points upon which the eye can rest is probably the reason that the "boiling" motion of our atmosphere is perceived in a much more marked manner over the white spot than on the adjoining sharply defined parts of the moon's surface. From this cause *Linné* appeared, on several occasions, as a mass of white cloud in motion, at the same time that the craters near it were seen steadily and with distinctness. This cloudy appearance arises probably from a peculiar, partly reflective property of the material of which

* Professor Bond states that "the moon, if the constitution of its surface resembled that of Jupiter, would photograph in one-fourteenth of the time it actually requires" (*Mem. Amer. Academy*, vol. viii., p. 284).

Linné consists. Some other portions of the moon's surface reflect light in an analogous manner.

At the time when the diagram was made, the shallow, saucer-like form of *Linné* was not seen, but I have detected it on other occasions. On the evening of July 8, at 7^h, when a great part of the light reflected from our atmosphere was removed by means of a Nicol's prism placed next to the eye, I observed a shadow within the western margin of the shallow crater.

In the centre nearly of *Linné*, but rather nearer to the western margin, was seen the small crater, as it is represented in the diagram.* This object was well defined in the telescope. The interior of the small crater was in shadow, with the exception of a small part of it towards the east. The margin of the small crater was much brighter on the western side, and at this part appears to be more elevated above the surface of *Linné*. Under very oblique illumination this high western wall appears, as a small brilliant eminence, and casts a shadow which is somewhat pointed. In consequence of the presence of visitors in my observatory, I did not take measures of the small crater. I estimated its diameter to be rather greater than one-fourth of the diameter of the white spot.

On the evening of July 9, at 9^h, the following measures were taken of *Linné*, and of the small interior crater. Under a power of 500 diameters, with which the measures were made, the boundary of *Linné* does not end abruptly, but passes gradually into the darker surface of the *Mare Serenitatis*. The white spot is oblong, but is not a regularly formed oval. At some parts of its outline small projecting portions of the bright surface interrupt the regularity of its figure.

The small crater, which appears to be deep, has a narrow margin, brighter than the white spot on which it occurs. The measures of this crater include the narrow, bright margin.

Length of the bright spot	"	7·85
Breadth	"	6·14
Diameter of the small centre	"	1·71

* In the woodcut, the crater is a little too small in proportion to the white spot.



December 14, 1866.—I observed the moon with a Savart's polariscope attached to the telescope. The coloured bands passed unbroken across *Linné*, which appeared at the time as a white spot. Also when a double-image prism and plate of quartz were used, *Linné* was coloured similarly to the adjoining parts. The light from *Linné* contained a smaller amount of polarised light.

February 14, 1867.—I examined carefully the spectrum of the light reflected from *Linné*. The small size of the object makes this observation somewhat uncertain. The lines of Fraunhofer were seen with great distinctness in the spectrum of the moon's light; but I failed to detect any lines which do not belong to solar light in the narrow brighter spectrum which was formed by the light from *Linné*.

Herr Schmidt is of opinion that a great change has recently taken place in the appearance of *Linné*, when it is viewed under oblique illumination. This conclusion is based upon a comparison of its present appearance, with the descriptions of Lohrmann and Mädler, and with Herr Schmidt's own observations from 1841 to 1843.*

On this account it is of importance to note that the earlier observations by Schröter seem to agree very closely with the appearance which *Linné* now presents.

In Plate IX. of Schröter's *Selenotopographische Fragmente* the place occupied by *Linné* is marked by a round white spot, and not by the figure of a crater. This white spot is a little smaller than the figure of the crater *Sulpicius Gallus*. The spot is distinguished on the Plate by the letter *v*.

At page 181, Schröter gives the following description of this object: "Die sechste Bergader kommt von einer fast dicht an den südlichen Gränzgebirgen befindlichen, verhältnissmäßig gezeichneten Einsenkung *u*, streicht nördlich nach *v*, woselbst sie wieder eine ohngefähr gleich grosse, aber ganz flache, als ein weisses, sehr kleines rundes Fleckchen erschienende, etwas ungewisse Einsenkung in sich hat. . . ."

I have put in Italics the words which apply to *Linné*. The observation was made, November 5, 1788, from 4^h 30^m to 8^h. The mean time of the observations was 7 days 14 hours after new moon. Schröter employed a power of 161 on his 7-foot reflector.†

The description of this object as "a flat, somewhat doubtful crater, which

* *Monthly Notices*, vol. xxvii., p. 93. *Astronom. Nachrichten*, No. 1631. *Sitzungsberichte der K. Akademie, Wien*, Bd. lv., February 1867.

† For his measures of the *Mare Serenitatis*, Schröter employed a reduced power of 95 diameters. In his second volume, at p. 276, he gives an account of a re-examination of this part of the moon's surface with more powerful telescopes. On this occasion (see Tab. lxix.) *Linné* was not observed, probably because it was too close to the terminator. Schröter remarks, ". . . indem noch nicht einmahl die ganze Fläche erleuchtet war, sondern die Lichtgränze östlich durch sie vor den östlichen Gränzgebirgen weg lag."

appears as a round white spot," agrees remarkably with the appearance which *Linné* now presents under similar conditions of illumination. The absence of any mention by Schröter of the small interior crater cannot be regarded as evidence of much weight, that this little crater has been subsequently formed. An object so small might easily have been overlooked by Schröter. However, Lohrmann's description in 1823,* and that of Mädler in 1831, do not appear to be in accordance with Schröter's observations, or with the present condition of the object.† The observations were made with a refractor of 8 inches aperture, and with various powers from 200 diameters to 800 diameters.

NOTE ON THE SPECTRUM OF URANUS (AND THE SPECTRUM OF COMET I)

(From *Proc. Roy. Soc.*, vol. xix., p. 488, 1871) .

IN the paper "On the Spectra of some of the Fixed Stars,"‡ presented conjointly by Dr. Miller and myself to the Royal Society in 1864, we gave the results of our observations of the spectra of the planets Venus, Mars, Jupiter, and Saturn; but we found the light from Uranus and Neptune too faint to be satisfactorily examined with the spectroscope.

By means of the equatorial refractor of 15 inches aperture, by Messrs. Grubb and Son, recently placed in my hands by the Royal Society, I have succeeded in making the observations described in this paper of the remarkable spectrum which is afforded by the light of the planet Uranus.

It should be stated that the spectrum of Uranus was observed by Father Secchi in 1869.§ He says: "Le jaune y fait complètement défaut. Dans le vert et dans le bleu il y a deux raies très-larges et très-noires." He represents the band in the blue as more refrangible than F, and the one in the green as near E.

The spectrum of Uranus, as it appears in my instrument, is represented in the accompanying diagram. The narrow spectrum placed above that of Uranus gives the relative positions of the principal solar lines and of the two strongest absorption-bands produced by our atmosphere, namely, the group of lines a little more refrangible than D, and the group which occurs about

* "A is the second crater upon this plain—has a diameter which exceeds somewhat 1 mile, is very deep, and can be seen under every illumination."—*Topographie der Mondoberfläche*, p. 92, and Plate, section IV.

† A series of careful observations has been made by Professor Respighi, *Les Mondes*, 13 Juin, 1867. See also observations of M. Flammarion, *Comptes rendus*, 20 Mai, 1867, and of M. Wolf, *Comptes rendus*, 17 Juin, 1867.

‡ *Phil. Trans.*, 1864, p. 413; and for Mars, *Monthly Notices R.A.S.*, vol. xxvii., p. 178.

§ *Comptes rendus*, vol. lxviii., p. 761, and "Le Soleil," Paris, 1870, p. 354.

midway from C to D. The scale placed above gives wave-lengths in millionths of a millimetre.

The spectrum of Uranus is continuous, without any part being wanting, as far as the feebleness of its light permits it to be traced, which is from about C to about G.

On account of the small amount of light received from this planet, I was not able to use a slit sufficiently narrow to bring out the Fraunhofer lines. The positions of the bands produced by planetary absorption, which are broad and strong in comparison with the solar lines, were determined by the micrometer and by direct comparison with the spectra of terrestrial substances.

The spectroscope was furnished with one prism of dense flint-glass, having a refracting-angle of 60° , an observing telescope magnifying $5\frac{1}{2}$ diameters, and a collimator of 5 inches focal length. A cylindrical lens was used to increase the breadth of the spectrum.

The remarkable absorption taking place at Uranus shows itself in six

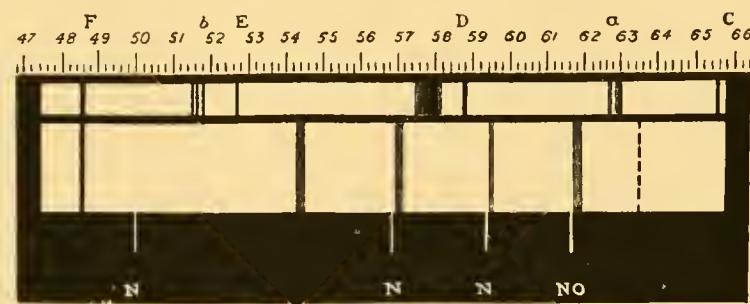


Fig. 47.

strong lines, which are drawn in the diagram. The least refrangible of these lines occurs in a faint part of the spectrum, and could not be measured. Its position was estimated only, and on this account it is represented in the diagram by a dotted line. The positions of the other lines were obtained by micrometrical measures on different nights. The strongest of the lines is that which has a wave-length of about 544 millionths of a millimetre.

The band at 572 of the scale is nearly as broad but not so dark; the one a little less refrangible than D is narrower than the others.

The measures taken of the most refrangible band showed that it was at or very near the position of F in the solar spectrum. The light from a tube containing rarefied hydrogen, rendered luminous by the induction-spark, was then compared directly with that of Uranus. The band in the planet's spectrum appeared to be coincident with the bright line of hydrogen.

Three of the bands were shown by the micrometer not to differ greatly in position from some of the bright lines of the spectrum of air. A direct comparison was made, when the principal bright lines were found to have the

positions, relatively to the lines of planetary absorption, which are shown in the diagram. The band, which has a wave-length of about 572 millionths of a millimetre, is less refrangible than the double line of nitrogen which occurs near it. The two planetary bands at 595 and 618 of the scale appeared very nearly coincident with bright lines of air. The faintness of the planet's spectrum did not admit of certainty on this point; I suspected that the planetary lines are in a small degree less refrangible. There is no strong line in the spectrum of Uranus in the position of the strongest of the lines of air, namely, the double line of nitrogen.

As carbonic-acid gas might be considered, without much improbability, to be a constituent of the atmosphere of Uranus, I took measures with the same spectroscope of the principal groups of bright lines which present themselves when the induction-spark is passed through this gas. The result was to show that the bands of Uranus cannot be ascribed to the absorption of this gas.

There is no absorption-band at the position of the line of sodium. It will be seen by a reference to the diagram that there are no lines in the spectrum of Uranus at the positions of the principal groups produced by the absorption of the earth's atmosphere.*

THE MOON

(From *Phil. Trans.*, 1880, Part II., 669)

During the last two years a large number of photographs of the light from limited areas of the lunar surface have been taken under very different conditions of illumination, and also during partial eclipses of the moon.

Most of these photographs present great differences in the relative general intensity of the ultra-violet region, but I have not been able to detect any indications of selective absorption. I am inclined to think that the differences of intensity of the more refrangible part of the spectrum which I have mentioned are not greater than may be accounted for on the ground of differences of intensity of the reflected light as a whole, and cannot therefore be taken as an evidence of the existence of a lunar atmosphere.

THE PLANETS

Venus.—Several photographs of this planet have been taken, together with a broad daylight spectrum. In the most perfect of these photographs, the Fraunhofer lines can be distinctly seen from *b* to *S* in the ultra-violet, and any differences, even if very slight, between the planetary spectra and the daylight spectrum, could be at once recognised. I cannot, however, discover any

* See pp. 378 and 384.

additional absorption lines, nor any modifications of the solar light. In our early eye-observations, Dr. Miller and myself failed to detect any change due to the atmosphere of this planet. The photograph shows even no strong general absorption of the blue and violet region.

Jupiter and Mars.—Similar photographs have been taken of these planets, but they fail to show any planetary modification of the solar light in the photographic region. In the visible region of the spectra of these planets, Dr. Miller and myself observed lines due to the atmospheres of these planets.*

NOTE ON THE PHOTOGRAPHIC SPECTRA OF URANUS AND SATURN

(From *Proc. Roy. Soc.*, vol. xlvi., p. 231, 1889)

URANUS.—In 1871 I had the honour to communicate to the Royal Society an account of the examination of the visible spectrum of Uranus.† The visible spectrum of this planet is remarkable, as it is seen to be crossed by several strong lines of absorption. Six of these dark bands are shown in a diagram which accompanies the paper, and their approximate positions in the spectrum are given. The spaces between the dark bands appear bright by contrast, and might suggest at first sight bright bands. I was unable to use a slit sufficiently narrow to enable me to determine whether the bright parts of the spectrum contain the Fraunhofer lines, which would be the case if Uranus, like the other planets, shines by reflected solar light.

The spectrum of this planet was carefully examined in 1872 by Vogel,‡ whose results are in accordance with my earlier ones. He observed some fainter lines or bands, in addition to those given in my paper. Vogel was unable to obtain evidence of the Fraunhofer lines. His observations agree with mine in placing a dark band at the position of F in the solar spectrum.§

In consequence of the Fraunhofer lines not having been seen, a presumption has arisen that Uranus may shine, in part at least, by emitted light.

It appeared to me that this question might be answered by photography. With an exposure of two hours, I obtained on June 3 a photograph of the spectrum of the planet from a little above F to beyond N in the ultra-violet. A pair of sky spectra, one on each side of the planet's spectrum, were taken on the same plate.

The spectrum of Uranus, though fainter, shows all the chief Fraunhofer lines seen in the comparison spectra, and is clearly solar. I have not been

* See later, pp. 383 and 385.

† *Proc. Roy. Soc.*, vol. xix., p. 488.

‡ "Untersuchungen über die Spectra der Planeten," Leipzig, 1874.

§ Measures of some of the bands were made at Greenwich in 1882. See "Greenwich Spectroscopic and Photographic Results," 1882, p. 33.

able to detect any indications of bright lines, nor of any strong bands or groups of absorption, such as those in its spectrum from F to C.

There can be no doubt that the spectrum of Uranus, at least, from a little above F to beyond N in the ultra-violet, is due to reflected solar light. I have not yet been able to re-examine the visible spectrum of the planet.

Saturn.—In 1864 I gave an account of an examination of the visible spectrum of this planet and its rings. In my paper on the "Photographic Spectra of Stars," * I described the photographic spectra of Venus, Jupiter, and Mars. About a year later I took a photograph of the spectrum of Saturn and his rings, but as it did not present any new features, but was purely solar, I have not given any description of it.

The favourable position of Saturn this year for obtaining a photograph in which the spectra of the ansæ of the rings could be seen distinct from the spectrum of the ball and of the part of the ring crossing it, determined me to take some photographs of the planet and its rings.

I have adopted the plan described in 1880, in which the planet is photographed while the sky is sufficiently bright to give a faint daylight spectrum on the plate. Any additional lines or other modifications of solar light due to the planet's atmosphere can in this way be easily detected.

In the photographs taken this year the slit was so placed upon Saturn that the spectrum consists of three distinct parts, the middle part being formed by the light from the ball, and the part of the ring across it, and on both sides of this spectrum the spectra of the ansæ. The planet was kept upon the same part of the slit with sufficient exactness to keep these three spectra distinct, and from encroaching upon each other, and therefore, if any difference existed between them, it could be detected.

The exact correspondence of the Fraunhofer lines in the spectrum of the planet and its rings with those of the sky spectrum is clearly shown, but I am unable now, as I was in 1881, to detect any lines, dark or bright, other than those which are also present in the sky spectra. The spectrum on the plate extends from a little above F to beyond N in the ultra-violet.

I am trying to obtain enlargements of the spectra of Saturn and Uranus to serve as illustrations to this note. If they can be done so as to admit of reproduction, I will do myself the honour to present them to the Royal Society.

[We have observed since, the visible spectrum of Uranus, but under unfavourable conditions, the planet being low and the sky not dark. These observations confirm me strongly in the opinion I formed in 1871 that the brighter parts of the spectrum appear so as an effect of contrast, and do not represent emitted light. In the moments of best vision the spectrum on both

* *Phil. Trans.*, 1880, p. 669.

sides of the brighter parts appeared to be darkened by groups of lines which give a heightened effect by contrast to the less obscured parts between them.

At moments, we were conscious of dark lines crossing the spectrum, but the unfavourable conditions under which the observations were made prevented us from ascertaining, by measurement or otherwise, whether any of these lines were Fraunhofer lines.—July 5.]

NOTE ON THE ATMOSPHERIC BANDS IN THE SPECTRUM OF MARS

(From *Astrophys. Journ.*, vol. i., p. 193, 1895)

THE question of any part of the bands seen by me in 1862–1867 in the spectrum of Mars being really due to the planet's atmosphere having been raised by the recent observations of Professor Campbell, we have taken the opportunity of Mars and the moon being visible together on the same nights to repeat my early observations.

The method employed by me in 1867 to eliminate the effect of the absorption of our own atmosphere from the planet's spectrum was to compare with it on the same night the spectrum of the moon when at a similar or lower altitude (*Month. Not.*, vol. xxvii., p. 178). In my later work on the planets by photography, in 1879, another plan was adopted, namely, to take the photographs when the twilight was just strong enough to give upon the plate the spectrum of the sky close about the planet, without enfeebling too much that of the planet itself (*Phil. Trans.*, 1880, p. 687).

On November 8, 1894, six photographs of the moon's spectrum and four of the spectrum of Mars were taken with different exposures, giving a range of spectrum from F to S in the ultra-violet. They were afterwards compared by placing a Mars' spectrum upon a moon's spectrum; but in accordance with my photographs of 1879 no bands, or other modification of the lunar spectrum strong enough to be detected in the photographs, could be discovered as peculiar to the planet's spectrum.

On November 8, 10, and 15 we compared by eye the spectrum of Mars with that of the moon, and observations of the spectrum of Mars when near the meridian were made on December 15, 18, and 20. Great care and caution are necessary in attempting to estimate the relative intensities of faint bands in the spectra of objects so different as Mars and the moon, and which, though they can be observed within a few minutes of each other, cannot be viewed simultaneously. As the judgment of the eye is influenced by brightness and breadth of spectrum, care was taken to make the lunar spectrum as narrow and about as bright as that of Mars. On these three nights the atmospheric bands on both sides of D, to which our attention was almost exclusively directed,

varied considerably in intensity in the moon's spectrum, but were always estimated by us to be rather stronger in the spectrum of Mars. The particular terrestrial groups on which our estimations were chiefly based are the narrow band from λ 5928 to about λ 5935 and the stronger group nearer D at about λ 5910-5925.

We strongly suspected that the broad atmospheric group which includes D, and extends from about λ 5885 to λ 5905, was rather more distinct in the spectrum of Mars, the moon having a lower altitude at the time.

These comparisons were repeated several times on each night, and Mrs. Huggins' independent observations agreed with my own that the bands I have named were always rather more easily seen in the planet's spectrum than in that of the moon, even when at a lower altitude.

Though we reserve our final opinion as to whether there are any Martian bands which do not correspond with those of our own atmosphere, we think it well to put on record that we have little doubt of the existence of a band on the blue side of D, beginning at the stronger end at about λ 5860, and traceable to beyond λ 5840, which does not appear to be the same as any terrestrial group, and may, therefore, presumably be peculiar to the atmosphere of Mars. We took pains to be quite sure that we were not deceived by the solar lines at that place in the spectrum, which, indeed, are quite different in their relative arrangement. The visibility of this band is subject to great variation, depending, it may be, on the state of the planet's atmosphere. It was distinctly seen on November 10.

A long series of cloudy nights has unfortunately prevented us from making our observations more complete, but we think it undesirable to delay longer in stating that the result of our work is to leave a strong conviction in our minds that the spectroscope does show an absorption which is really due to the atmosphere of Mars (see p. 385).

LONDON, January 6, 1895.

PHOTOGRAPHIC SPECTRA OF THE PLANETS

(See *Astrophys. Journ.*, vol. i., pp. 196 and 273, 1895)

DURING the years 1880-1895, a number of photographs of the spectra of the planets were taken in the evenings, in most cases while the sky was sufficiently bright to give a spectrum for comparison on each side of the planet's spectrum; when this was not possible, the plate was left in the spectroscope, and a sky comparison spectrum taken on the following day. The spectroscope consisted of an Iceland spar prism and quartz lenses attached to the Cassegrain reflector, and the spectra extend from about λ 486 to about λ 320.

When in 1895 Professor Vogel was about to publish the results of the

observations on the spectra of the planets made at Potsdam, I placed my negatives in his hands that our spectra might be included in Professor Vogel's discussion. His paper appeared in the *Sitzungsberichte d. K.P. Akad. d. Wissenschaften*, 1895, ii., p. 10.

From a translation of Professor Vogel's paper in the *Astrophysical Journal* (vol. i., pp. 196 and 273, 1895) the quotations which follow have been taken:

"Mr. Huggins, to whom we are indebted for the first photographs of planetary spectra, has kindly placed at my disposal the whole of the valuable material which he has collected, and with regard to which he has hitherto published only some very general statements. I have accurately investigated all of the spectograms, and give the results of the investigation after those obtained at Potsdam. A description of the apparatus with which Huggins obtained his photographs of planetary spectra is to be found in his classical memoir, 'On the Photographic Spectra of Stars' (see p. 12).

"In order to obtain wave-lengths from the measures of the Huggins photographs, I constructed a curve based on the measurements of a number of plates on which the lines of the air spectrum are very strongly impressed."

Venus

"A photograph taken by Mr. Huggins in 1879 shows the spectrum of Venus together with that of the background of the sky. More than eighty lines can be distinguished in both spectra, and not the slightest anomaly can be found in the spectrum of the planet. The photographic spectrum extends from λ 480 to λ 320. The last portion above λ 328 in the spectrum of the planet, and above λ 334 in that of sky, is very weak."

Mars

"Mr. Huggins informs me that he obtained several photographs of the spectrum in November 1894, which extend beyond the violet, and which show no departure whatever from the solar spectrum. No photographs had been made by him before this time."

"As a supplement to the statements in my memoir respecting the observations of the visual spectrum made by Huggins in 1867, I have to add that Huggins has withdrawn the opinion which he expressed on the ground of his early observations—namely, that the predominant red colour of Mars is due to groups of lines in the blue and violet. The photographs completely remove the doubts which remained after the observations of Huggins as to whether the lines which he perceived in the more refrangible part of the spectrum were

special lines characteristic of the atmosphere of Mars, or merely the Fraunhofer lines, and their decision is in favour of the latter alternative."

"My early observations agreed with the observations of Huggins in showing that Mars has an atmosphere of similar constitution to our own; the existence is revealed by certain groups of lines in the vicinity of the C and D lines, and by the telluric groups *a* and *b*. Huggins was able to observe the planet when it was in a very favourable position."

"I have received from Huggins the following information with respect to the observations on the absorption lines of Mars made by himself and Mrs. Huggins in 1894. On November 8, 10, and 15, the spectrum of Mars was compared with that of the moon by both Mr. and Mrs. Huggins, and on December 15, 18, and 20, the spectrum of Mars was observed when the planet was nearly on the meridian. In the comparisons with the lunar spectrum, care was taken to observe the two spectra, which differed so greatly in breadth and intensity, under as far as possible equal conditions."

"On the three days of observation above mentioned the intensity of the atmospheric bands near D, which were the principal objects of study, varied considerably in the lunar spectrum; still, both observers, independently and accordantly, estimated that the groups of lines on which the comparison was chiefly based—a narrow band at λ 593 and a broader one at λ 592—were always stronger in the spectrum of Mars. In like manner the broad atmospheric group, which contains the D lines (λ 5887 to λ 5903), was repeatedly seen more distinct in the spectrum of Mars, although the moon was then at a low altitude."

"The observers desire to withhold their decision for the present as to whether there are absorption bands in the atmosphere of Mars which do not correspond with those in our own atmosphere; but they do feel justified in saying that they have little doubt of the existence of an absorption band which lies a little on the more refrangible side of D, extending from λ 586 to λ 584, and which has not yet been recognised as a telluric group. The lines which are found in this region in the solar spectrum have probably made the decision somewhat difficult, but they could hardly cause a serious mistake. The visibility of this band is subject to changes which, in the opinion of the observers, may depend upon conditions of the atmosphere of the planet."

Jupiter

"Two of the photographs of Jupiter taken by Huggins in 1878 represent its spectrum with that of the sky on each side. In one of the photographs the sky spectrum extends only a little beyond K, while the planetary spectrum is strong up to λ 333, and can be traced as far as λ 326. The weak sky

spectrum allows a comparison of only the principal lines of the two spectra. Comparison with the Atlas showed a complete coincidence of fifty-seven planetary and Fraunhofer lines. The second plate is not so good; only fifteen or twenty lines can be certainly recognised, which coincide perfectly with lines in the spectrum of the sky background."

Saturn

"Two photographs were taken by Huggins in 1887. One of them, taken on March 23 with an exposure of one hour, is remarkable for the great extension of the spectrum into the ultra-violet; it can be traced as far as $\lambda 315$. The slit was wide, and so only twelve lines can be recognised. A photograph of less excellence, taken on March 19 with about twenty minutes' exposure, shows only the lines H_γ , G, H, K, and two groups of lines in the ultra-violet.

"I have also six photographs taken by Huggins in 1889, which have an especial interest on account of the fact that the slit was so placed as to give the spectrum of the ansæ of the ring on each side of the spectrum of the ball. Not the least difference can be perceived between the spectra, which, on three of the plates especially, are distinctly separated.

"Three of the six photographs contain little detail, and only the principal lines can be seen in the spectrum of the planet, or in that of the sky background which accompanies it. A fourth plate, without comparison spectrum, shows twenty-two lines in the ultra-violet between H and $\lambda 344$. The spectrum can be traced as far as $\lambda 330$; altogether more than thirty Fraunhofer lines can be recognised. At H_γ and H there are dark bands on the negative which look as if they were caused by bright lines, as in the case of the Potsdam photograph. On the fifth plate they are wanting; the slit was decidedly narrower. The spectrum extends only a short distance into the ultra-violet. Altogether, twenty lines are visible in the planetary spectrum, the agreement of which with the solar spectrum is complete. On the sixth plate the lines which can be identified are more than twenty-six. All lines agree with those of the bright sky background. As I have already mentioned, the photographs of Huggins show definitely that there is no difference between the spectrum of the planet and that of the rings in the more refrangible part of the spectrum. The greater brightness of the rings, as compared with the planet for the chemically active rays, is naturally explained by the density of the atmosphere of the planet itself."

Uranus

"A successful photograph of the spectrum of Uranus, made by Huggins on June 3, 1889, with exposure of two hours, extends farther into the ultra-

violet than the one made at Potsdam. On this plate the maximum intensity is at G. There is a very beautiful sky spectrum, full of detail on each side of the planet's spectrum, which was obtained on the following morning with a narrower slit. Although no direct comparison can be made with the planetary spectrum, very desirable reference points are supplied. The measurements of this plate which I have made give the following wave-lengths of the lines, or of the bands caused by the blending of groups of lines in consequence of the rather wide slit. I have added the wave-lengths of the corresponding solar lines.

SPECTRUM OF URANUS	SPECTRUM OF SUN
3565 Band.	3567 Group of lines.
3580 Broad band.	3584 Group of broad lines.
363 Band.	3625 Middle of a broad band of several systems of lines.
3725 3737 } Lines just visible.	3722 3736 }
3750	3748 Group of strong lines.
3795 Band.	3795
3833 Broad band.	3833
3880 Weak band.	3879 Strong line in a group of rather strong lines.
3935 } Broad bright band (on negative).	3934 K.
3972 } Distinct line.	3969 H.
4101 Distinct line.	4102 Strong line h.
4305 Broad band, diffuse toward violet.	4305 Middle of Group G.
4322	4325 Strong line in a group.
4340	4341 Strong line H _y and group.
486	4862 F.

"The photographs taken in Potsdam and in London supplement each other admirably, and together furnish a proof that the more refrangible portion of the spectrum of Uranus contains neither absorption bands nor bright lines; hence the assertion of Lockyer that the spectrum of Uranus is to be regarded as an emission spectrum is entirely without foundation."

NOTE ON THE ABSORPTION LINES NEAR D IN THE SPECTRUM OF MARS, WHICH ARE APPARENTLY IDENTICAL WITH THOSE DUE TO WATER VAPOUR IN OUR ATMOSPHERE

THE observations recorded in the preceding papers, as well as the independent observations of Vogel, Scheiner, and others at Potsdam, appeared to afford strong evidence for the existence of the vapour of water in the atmosphere of Mars.

Against this view, Campbell, in 1894, looked in vain for these lines at the Lick Observatory, and his spectrophotographs taken in 1896 did not show

them. Previously, at the Lick, Keeler was not able to detect them. Later, special attempts to observe these lines in the spectrum of Mars at the Pic du Midi, under favourable circumstances, also failed.

The existence in the spectrum of Mars of these absorption lines near D, as well as the stronger band of water vapour at α , has now been satisfactorily shown at the Lowell Observatory, Flagstaff, Arizona, by means of photographic plates specially sensitive to the red end of the spectrum. The results so far, according to Slipher, are compatible with snow-caps and a comparatively moderate temperature on Mars (*Comptes rendus*, t. cxlvi., p. 547, March, 1908; and *Astrophys. Journ.*, vol. xxvii., p. 397). Prof. Very's conclusions from measurements of the intensification of the aqueous bands in the spectrum of Mars, on the Lowell plates, give for Mars one and three-quarters the aqueous absorbent mass over Flagstaff. Further, that the average layer of precipitable water on Mars may be taken as equal to 14 mm., while the mean value for the earth is probably three or four times as great (*Bull. Lowell Observatory*, No. 36, 1909).

“ON THE WAVE-LENGTH OF THE PRINCIPAL LINE IN THE
SPECTRUM OF THE AURORA”

(From *Proc. Roy. Soc.*, vol. xlvi., p. 430, 1889)

NOTWITHSTANDING the large number of determinations by different observers, since Ångström in 1867, of the wave-length of the principal (and frequently the only) line in the spectrum of the Aurora, this value has not yet been accepted as definitely fixed with the degree of accuracy which is required for a final inquiry into its chemical origin. The uncertainty within rather wide limits, which seems still to obtain, has arisen mainly from the circumstance that in nearly all cases the observations have been made with a small direct-vision spectroscope, and under conditions which do not admit of an accurate determination of the value sought for. About half the number of some twenty-four observers agree pretty well, but among the results given by the others the differences are very large in relation to the accuracy which is required, though they are not greater, perhaps, than was to be expected from the circumstances under which the observations were made.

I think it is very desirable, therefore, that I should put on record some observations of the spectrum of the Aurora which I made in the year 1874, but which up to the present time have remained unpublished. These observations were made with a powerful spectroscope, and under conditions which enabled me to determine the wave-length of the principal line within narrow limits of error. The spectroscope was made by Sir Howard Grubb on the automatic principle of his father, Mr. Thomas Grubb. It is furnished with two “Grubb”

compound prisms; each has 5 square inches of base, and gives nearly twice the dispersion of a single prism of 60° —namely, about $9^\circ 6'$ from A to H.

The object-glasses of the collimator and telescope are 1·25 inch in diameter. The definition is very good. Though the automatic arrangement works well, I always take the precaution to measure only small differences of position of the line to be determined from lines near it, the wave-lengths of which are known.

The observations were made on February 4, 1874. There was a brilliant Aurora, showing a whitish light; a direct-vision spectroscope resolved this light into a brilliant line in the yellow and a faint continuous spectrum.

The "Grubb" spectroscope was directed from the window of the observatory upon the brightest part of the Aurora. In the first instance, an estimation by eye was made of the position of the bright line by comparing it in the instrument with the spectrum of a spirit lamp. The bright line was seen to fall on the more refrangible side of the line for which Watts gives the wavelength 5582,* Ångström and Thalén 5583,† by from one-fifth to one-fourth of the distance of this line from the beginning of the band. If we take one-fourth, we have λ 5569·6; one-fifth gives λ 5572·3. The mean of these values gives for the

$$\text{Aurora line } \lambda 5570\cdot9 \dots \dots \dots \dots \quad (1)$$

The cross-wires of the spectroscope were then brought upon the line, and the reading 3476 showed the line to fall about midway between two strong lines in the spectrum of tin, λ 5564 and λ 5587 respectively, according to my measures.‡ The position of the cross was then compared directly with those lines in the spectrum of an induction spark taken between electrodes of tin. The further details of this comparison are not given in my note-book, but the result only, which placed the

$$\text{Aurora line at } \lambda 5571 \dots \dots \dots \dots \quad (2)$$

Consulting my map of the chemical elements, I found that there was a line of tellurium very near this place—namely, at λ 5575. I therefore brought the spark from tellurium before the slit, when the cross appeared on the more refrangible side of the tellurium line. The measure of the distance of the cross from this line came out equal to λ 0003. The place given in my paper for this line of tellurium is 5575. Thalén gives for the same line 5574·1.§ If we take the mean of these values and deduct 0003, we get for

$$\text{The line of the Aurora } \lambda 5571\cdot5 \dots \dots \dots \quad (3)$$

* *Phil. Mag.*, vol. xli., 1871, p. 14.

† "Spectres des Métalloïdes," *Nov. Act. Soc. Sci. Upsal.*, vol. ix., 1875, p. 29.

‡ "Spectra of the Chemical Elements," *Phil. Trans.*, 1864, p. 139.

§ *Brit. Assoc. Report*, 1885, p. 292.

There are strong lines of iron very near this position in the spectrum, and I made use of these also for a further determination of the place of the Aurora line. The cross, after having been placed upon the line of the Aurora, was confronted with these lines in the spectrum of iron.

The condensed account in my note-book does not give further particulars of this comparison, but states only that the place of the

$$\text{Aurora line came out } \lambda 5571\cdot 5 \dots \dots \dots \quad (4)$$

Summing up these determinations we have—

(1) Eye-estimation	$\lambda 5570\cdot 9$
(2) From tin	$5571\cdot 0$
(3) From tellurium	$5571\cdot 5$
(4) From iron	$5571\cdot 5$

From these values I think that we are justified in taking for the Aurora line, as a position very near the truth,

$$\lambda 5571 \pm 0\cdot 5 \dots \dots \dots \dots \dots \quad (5)$$

Among the numerous determinations of other observers, those of Professor H. C. Vogel in 1872 * seem to me to have great weight. A direct-vision spectroscope with a set of five prisms was used. The reduction of the readings of the micrometer into wave-lengths was based upon the repeated measures of 100 lines of the solar spectrum.

The screw had been thoroughly examined. After each observation of the Aurora line, readings were taken of the lines of sodium or of hydrogen. The observations extended over four nights. On three nights four separate readings were obtained; on the fourth night two only. Vogel gives as the mean result of the fourteen observations—

$$\text{Aurora line } \lambda 5571\cdot 3 \pm 0\cdot 92 \dots \dots \dots \dots \quad (6)$$

Perhaps I should state that I find, from a remark in my note-book, that at the time of my observations in 1874 I was not aware of Vogel's results, and I could not, therefore, have been biassed in any way by them.

The recent observations on the spectrum of the Aurora by Gyllenskiöld, at Cap Thordsen, in 1882, deserve special mention.† With a Hoffmann spectroscope, furnished with a scale, he obtained at Cap Thordsen, in 1882, a mean result of $\lambda 5568 \pm 1\cdot 6$; later, in 1884, at Upsala, with a Wrede spectroscope furnished with a micrometer screw, a mean value for the Aurora line

* *Leipzig. Math. Phys. Berichte*, vol. xxii., p. 285.

† "Observations faites au Cap Thordsen, Spitzberg, par l'Expédition Suédoise," vol. ii., I. : *Aurores Boréales*, par Carlheim-Gyllenskiöld. Stockholm, 1886.

$\lambda 5569 \pm 6.2$.* Gyllenskiöld discusses in detail nearly all the recorded observations of the spectrum of the Aurora from 1867 to 1882, and then brings them together in a table, with such probable errors as the original statements of the observers enabled him to assign to them. I think it is desirable to give that part of his list which contains the observations of the brightest line:—

1867.	Ångström	Upsal	$\lambda 5567 \pm 1.0$
1868.	Struve	Poulkowa	5552 ± 14.9
	Lemström	Tromsoe	5659 ± 14.0
1869.	Peirce	États-Unis	5565 ± 10.8
1870.	Proctor	5595 ± 25.0
1871.	Smyth	Édimbourg	5579 ± 9.5
	Lindsay	Aberdeen	5680 ± 50.0
	Barker	New Haven	5594 ± 13.0
1872.	Vogel	Kiel	5571 ± 0.9
	Denza	Moncalieri	5568 ± 11.9
	Donati	Florence	5569 ± 10.0
	Oettingen	Dorpat	5548 ± 30.0
	Respighi	Rome	5574 ± 10.0
	Wijkander	Spitzberg	5572 ± 1.0
1873.	Backhouse	Sunderland	5660 ± 10.0
	Barker	New Haven	5569 ± 13.9
	Lemström	Enare	5569 ± 0.5
1874.	Backhouse	Sunderland	5570 ± 10.0
	Maclear	"Challenger"	5522 ± 37.1
1879.	Nordenskiöld	Pitlekaïe	5563 ± 10.0
1880.	Copeland	Dunecht	5572 ± 2.0
1882.	Gyllenskiöld	Cap Thordsen	5568 ± 1.6
1884.	„	Upsal	5569 ± 6.2

Gyllenskiöld then calculates by the method of least squares the mean value of all the determinations, and finds the following result †:

$$\text{Mean value of the 23 observations, } \lambda 5570.0 \pm 0.88 \quad \dots \quad (7)$$

The recent measures by C. C. Krafft,‡ depart largely from Gyllenskiöld's mean value. Krafft found on

1882, November 2	$\lambda 5595$
„ „ 11	5586

and measures with the same instrument made by Schröter on November 17 gave $\lambda 5587$.

Now, though Ångström's original value $\lambda 5567$ may not be quite accurate, his observation fixed a limit towards the red beyond which the Aurora line cannot lie. Ångström says, "Sa lumière était presque monochromatique, et

* "Observations faites au Cap Thordsen, Spitzberg," vol. ii., p. 166.

† *Ibid.*, p. 169.

‡ "Beobachtungs-Ergebnisse der Norwegischen Polarstation," etc. A. S. Steen. Christiania, 1888.

consistait d'une seule raie brillante située à gauche" (on the more refrangible side) "du groupe connu des raies du calcium."* The position of the most refrangible line of this calcium-group is accurately known; according to †

Kirchhoff	$\lambda 5580\cdot 9$
Thalén	$5580\cdot 9$
Huggins	$5581\cdot 0$

It is certain, therefore, from Ångström's first observation in 1867 alone, that the Aurora line lies well on the more refrangible side of wave-length 5580. This limit towards the red was confirmed afterwards by Ångström himself; he says later that the yellow line falls almost midway between the second and third line of the shaded carbon group.‡ The positions of these lines of comparison are, according to Ångström and Thalén, $\lambda 5538$ and $\lambda 5583$.§

It follows that Krafft's values, $\lambda 5586$, $\lambda 5587$, and $\lambda 5595$, must be from some cause inaccurate. A possible explanation may be found in the small number of solar lines employed by Krafft for the reduction of the measures into wave-lengths. The curve was drawn through the six Fraunhofer lines, B, C, *a*, D, E, and *b*. There was no control for the curve between D and E, and a very small deviation of the curve from its true position here would be sufficient to account for the position of less refrangibility of from $\lambda 0016$ to $\lambda 0024$, which his measures give for the Aurora line.

It should be stated that Krafft expresses regret that more attention could not be given to the spectroscopic observations. He says: "Leider gestatteten die obligatorischen Beobachtungen nicht, den spectroscopischen Untersuchungen die gehörige Aufmerksamkeit angedeihen zu lassen. . . . Ich glaubte ausserdem diese Messungen um so mehr auslassen zu können, als der Platz der gewöhnlichen Nordlichtlinie oft und sehr genau bestimmt ist."

To sum up, we have the following values for the principal line of the Aurora:

(6) 1872, Vogel	$\lambda 5571\cdot 3 \pm 0\cdot 92$
(5) 1874, Huggins	$5571\cdot 0 \pm 0\cdot 5$
(7) Gyllenskiöld's mean of 23 observers from 1867 to 1884	$5570\cdot 0 \pm 0\cdot 88$

These values agree closely, and fix within very narrow limits the position in the spectrum where we have to seek the chemical origin of the line.

Gyllenskiöld, from his observations of the changes which occur in the spectrum of the Aurora, comes to the conclusion that: "le spectre de l'Aurore boréale résulte de la superposition de plusieurs spectres différents," and that

* "Spectre solaire," Upsal, 1868, p. 42.

† *Brit. Assoc. Rep.*, 1884, p. 372.

‡ *Nature*, vol. x., p. 211.

§ *Acta Upsal.*, vol. ix., 1875 (p. 29).

"la raie principale forme un de ces spectres élémentaires ; elle apparaît très souvent seule." A similar view was taken many years ago by Ångström* and by Vogel.†

[After consideration, I think that I ought to point out that Mr. Lockyer's recent statement ‡ that : "The characteristic line of the aurora is the remnant of the brightest manganese fluting at 558," is clearly inadmissible, considering the evidence we have of the position of this line.

In support of this statement Mr. Lockyer says : "Ångström gave the wave-length of the line as 5567, and since then many observers have given the same wave-length for it, but probably without making independent determinations. Piazzi Smyth, however, gives it as 558, which agrees exactly with the bright edge of the manganese fluting. R. H. Proctor also gives the line as a little less refrangible than Ångström's determination. He says : 'My own measures give me a wave-length very slightly greater than those of Winlock and Ångström' (*Nature*, vol. iii., p. 568).".

By reference to Gyllenskiöld's table it will be seen that the probable errors of the determinations by Piazzi Smyth and Proctor, 5579 ± 9.5 and 5595 ± 25.0 respectively,§ are too large to entitle these measures to special weight.

Mr. Lockyer says further : "Gyllenskiöld's measures with the Wrede spectroscope also give 5580 as the wave-length of the characteristic line. I feel justified, therefore, in disregarding the difference between the wave-length of the edge of the manganese fluting and the generally accepted wave-length of the aurora line."

Gyllenskiöld's single measure of 5580, on which Mr. Lockyer relies, differs widely from the values which Gyllenskiöld himself assigns to this line, namely, from observations at Cape Thordsen in 1882, $\lambda 5568 \pm 1.6$, and from observations at Upsala in 1884, with the Wrede spectroscope, $\lambda 5569 \pm 6.2$.

Speaking of Krafft's observations, Mr. Lockyer says :|| "The wave-lengths obtained for the aurora line were 5595, 5586, and 5587. Unlike most observations, these place the aurora line on the less refrangible side of the manganese fluting. Hence, we have an additional reason for neglecting the difference between the wave-length of the brightest edge of the manganese fluting, and the commonly accepted wave-length of the aurora line, as given by Ångström. . . . These observations are the latest which have been published, and were

* *Nature*, vol. x., p. 210.

† *Leipzig. Math. Phys. Berichte*, vol. xxiii., p. 298.

‡ *Proc. Roy. Soc.*, vol. xlvi. (1889), p. 234.

§ Gyllenskiöld's statement of Proctor's value is based on *Nature*, vol. iii., p. 347 and p. 68.

|| *Proc. Roy. Soc.*, vol. xlvi. (1889), p. 241.

obviously made with a full knowledge of all previous work, so that their importance must be strongly insisted upon."

I have already pointed out that Krafft's measures were not made under circumstances which assured to them a high degree of accuracy; and Krafft's own words, which I have quoted, disclaim expressly any special attempt on his part to redetermine the position of the principal line with a higher degree of accuracy than the observers who preceded him.—March 4.]

Section IX
CHEMICAL SPECTRA

LIST OF PAPERS

- “On the Spectra of some of the Chemical Elements.”
Phil. Trans., vol. cliv., pp. 139–160. *Phil. Mag.*, vol. xxvii., p. 541, 1863. P. 397.
- “Note on the Spectra of Erbia and some other Earths.”
Proc. Roy. Soc., vol. xviii., p. 546, 1870. P. 422.
- “On the Spectrum of the Flame of Hydrogen.” (Spectrum of Water Vapour.)
Proc. Roy. Soc., vol. xxx., p. 576, 1880. P. 429.
- “On the Relative Behaviour of the H and K Lines in the Spectrum of Calcium.” (And Mrs. Huggins.)
Proc. Roy. Soc., vol. lxi., p. 433, 1897. P. 433.
- “Preliminary Note on some Modifications of the Mg Line at λ 4481 under different Laboratory Conditions of the Spark Discharge.” (And Lady Huggins.)
Astrophys. Journ., vol. xvii., No. 2 (March 1903), p. 145, 1903. P. 442.
- “On the Spectrum of the Spontaneous Luminous Radiation of Radium at Ordinary Temperatures.” (And Lady Huggins.)
Proc. Roy. Soc., vol. lxxii., p. 196, 1903. P. 444.
- “Further Observations of the Spectrum of the Spontaneous Luminous Radiation of Radium at Ordinary Temperatures.” (And Lady Huggins.)
Proc. Roy. Soc., vol. lxxii., p. 409. P. 448.

"On the Spectrum of the Spontaneous Luminous Radiation of Radium :
Part III., Radiation in Hydrogen." (And Lady Huggins.)
Proc. Roy. Soc., vol. lxxvi., p. 488, 1905. P. 453.

"On the Spectrum of the Spontaneous Radiation of Radium: Part IV.,
Extension of the Glow." (And Lady Huggins.)
Proc. Roy. Soc., vol. lxxvii., p. 130, 1905. P. 457.

HISTORICAL STATEMENT

(From *Nineteenth Century Review*, June 1897)

AT that time (1863) no convenient maps of the spectra of the chemical elements, which were then but imperfectly known, were available for comparison with the spectra of the stars. Kirchhoff's maps were confined to a few elements, and were laid down on an arbitrary scale, relatively to the solar spectrum. It was not always easy, since our work had to be done at night, when the solar spectrum could not be seen, to recognise with certainty even the lines included in Kirchhoff's maps. To meet this want, I devoted a great part of 1863 to mapping, with a train of six prisms, the spectra of twenty-six of the elements; using as a standard scale the spark-spectrum of common air, which would be always at hand. The lines of air were first carefully referred to those of purified oxygen and nitrogen. The spectra were obtained by the discharge of a large induction coil furnished with a condenser of several Leyden jars. I was much assisted by the specimens of pure metals furnished to me by Dr. W. A. Miller and Dr. Matthiessen.

ON THE SPECTRA OF SOME OF THE CHEMICAL ELEMENTS

(From *Phil. Trans.*, vol. cliv., pp. 139–160, and *Phil. Mag.*, vol. xxvii., p. 541, 1863)

I HAVE been engaged for some time, in association with Professor W. A. Miller, in observing the spectra of the fixed stars. For the purpose of accurately determining the position of the stellar lines, and their possible coincidence with some of the bright lines of the terrestrial elements, I constructed an apparatus in which the spectrum of a star can be observed directly with any desired spectrum. To carry out this comparison, we found no maps of the spectra of the chemical elements that were conveniently available. The minutely detailed and most accurate maps and tables of Kirchhoff were confined to a portion of the spectrum, and to some only of the elementary bodies; and in the maps of both the first and the second part of his investigations, the

elements which are described are not all given with equal completeness in different parts of the spectrum. But these maps were the less available for our purpose because, since the bright lines of the metals are laid down relatively to the dark lines of the solar spectrum, there is some uncertainty in determining their position at night, and also in circumstances when the solar spectrum cannot be conveniently compared simultaneously with them. Moreover, in consequence of the difference in the dispersive power of prisms, and the uncertainty of their being placed exactly at the same angle relatively to the incident rays, tables of numbers obtained with one instrument are not alone sufficient to determine lines from their position with any other instrument.

It appeared to me that a standard scale of comparison such as was required, and which, unlike the solar spectrum, would be always at hand, is to be found in the lines of the spectrum of common air. Since in this spectrum about a hundred lines are visible in the interval between α and H, they are sufficiently numerous to become the fiducial points of a standard scale to which the bright lines of the elements can be referred. The air-spectrum has also the great advantage of being visible, together with the spectra of the bodies under observation, without any increased complication of apparatus.

2. The optical part of the apparatus employed in these observations consists of a spectroscope of six prisms of heavy glass. The prisms were purchased of Mr. Browning, optician, of the Minories, and are similar in size and in quality of glass to those furnished by him with the Gassiot spectroscope. They all have a refracting angle of 45° . They increase in size from the collimator; their faces vary from $1\cdot7$ by $1\cdot7$ inch to $1\cdot7$ by 2 inches.

The six dispersing prisms and one reflecting prism were carefully levelled, and the former adjusted at the position of minimum deviation for the sodium line D. The train of prisms was then enclosed in a case of mahogany, marked α in the diagram, having two openings, one for the rays from the collimator b and the other for their emergence after having been refracted by the prisms. These openings are closed with shutters when the apparatus is not in use. By this arrangement the prisms have not required cleansing from dust, and their adjustments are less liable to derangement. The collimator b has an achromatic object-glass by Ross of $1\cdot75$ inch diameter, and of $10\cdot5$ inches focal length. The object-glass of the telescope, which is of the same diameter, has a focal length of $16\cdot5$ inches. The telescope moves along a divided arc of brass, marked in the diagram c . The centre of motion of the telescope is nearly under the centre of the last face of the last prism. The eyepiece was removed from the telescope, and the centre of motion was so adjusted that the image of the illuminated lens of the collimator, seen through the train of prisms, remained approximatively concentric with the object-glass of the telescope.

whilst the latter was moved through an extent of arc equal to the visible spectrum. All the pencils emerging from the last prism, therefore, with the exception of those of the extreme refrangible portion of the spectrum, are received nearly centrically on the object-glass of the telescope. The total deviation of the light in passing through the train of prisms is, for the ray D,

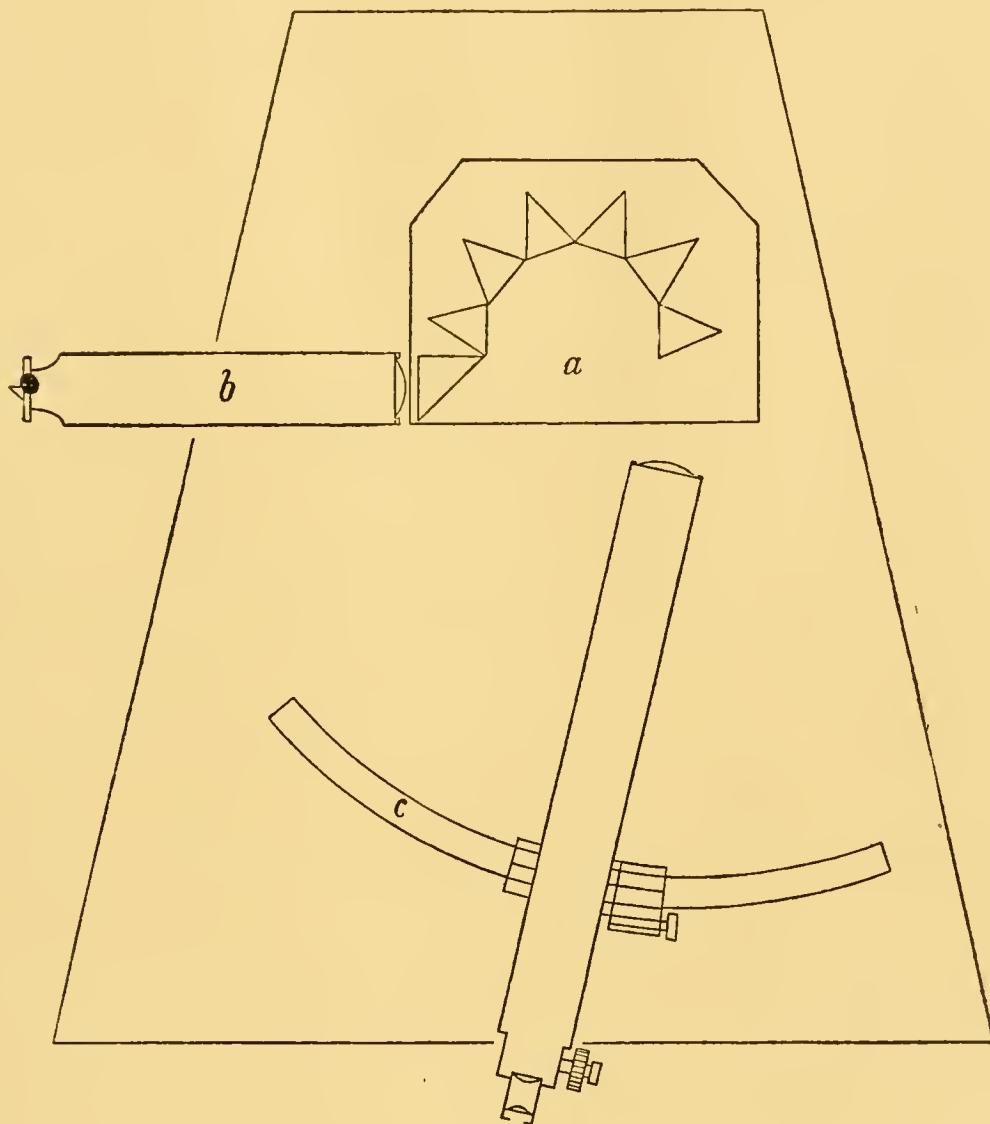


Fig. 48.

about 198° . The interval from A to H corresponds to about $21^\circ 14'$ of arc upon the brass scale.

3. The measuring-part of the apparatus consists of an arc of brass, marked *c* in the figure, divided to intervals of $15''$. The distance traversed by the telescope in passing from one to the other of the components of the double

sodium line D, is measured by five divisions of $15''$ each. These are read by a vernier.

Attached to the telescope is a wire micrometer by Dollond. This records 60 parts of one revolution of the screw for the interval of the double sodium line. Twelve of these divisions of the micrometer, therefore, are equal to one division of the scale upon the arc of brass. The micrometer has a cross of strong wires placed at an angle of 45° nearly with the lines of the spectrum. The point of intersection of these wires may be brought upon the line to be measured by the micrometer screw, or by a screw attached to the arm carrying the telescope. For the most part the observations were read off from the scale, and the micrometer has been only occasionally employed in the verification of the measures of small intervals. The sexagesimal readings of the scale, giving five divisions to the interval of the double line D, have been reduced to a decimal form, the units of which are intervals of $15''$, and these are the numbers given in the tables. An attempt was made to reduce the measures to the scale of Kirchhoff's Tables, but the spectra are not found to be superposable on his. This is due, in great part, probably to the prisms in his observations having been varied in their adjustment for different parts of the spectrum. The eyepieces are of the positive form of construction. One, giving the power of 15, is by Dollond; the other, of about 35, is by Cooke.

4. The excellent performance of the apparatus is shown by the great distinctness and separation of the finer lines of the solar spectrum. All those mapped by Kirchhoff are easily seen, and many others in addition to these. The *whole* spectrum is very distinct. The numerous fine lines between α and A are well defined. So also are the groups of lines about and beyond G. H is seen, but with less distinctness.

As, with the exception of the double potassium line near A, no lines have been observed less refrangible than α , the maps and tables commence with the line α of the solar spectrum, and extend to H.

The observations are probably a little less accurate and complete near the more refrangible limit. Owing to the feebleness of the illumination of this part of the spectrum, the slit has to be widened, and moreover, the cross-wires being seen with difficulty, the bisection of a line exactly is less certain.

5. For all the observations the spark of an induction coil has been employed. This coil has about fifteen miles of secondary wire, and was excited by a battery of Grove's construction, sometimes two, at others four cells having been employed. Each of these cells has 33 square inches of acting surface of platinum. With two such cells the induction spark is 3 inches in length. A condenser is connected with the primary circuit, and in the secondary a battery of Leyden jars is introduced. Nine Leyden jars, each surface of each of which exposes 140 square inches of metallic coating, were employed. These

are arranged in three batteries of three jars each, and the batteries are connected in polar series.

The metals were held in the usual way with forceps. The nearness of the electrodes to each other, their distance from the slit, and the breadth of the latter were varied to obtain in each case the greatest distinctness. The amount of separation of the electrodes was always such that the metallic lines under observation extended across the spectrum. The two sets of discharging-points were arranged in the circuit in series.

6. Some delay was occasioned by the want of accordance of the earlier measures, though the apparatus had remained in one place and could have suffered no derangement. These differences are supposed to arise from the effect of changes of temperature upon the prisms and other parts of the apparatus. This source of error could not be met by a correction applied to the zero-point of measurement, as the discordances observed corresponded, for the most part, to an irregular shortening and elongation of the whole spectrum.

The principal air-lines were measured at one time of observing, during which there was satisfactory evidence that the values of the measures had not sensibly altered; and these numbers have been preserved as the fiducial points of the scale of measures. The lines of the spectra of the metals have been referred to the nearest standard air-line, so that only this comparatively small interval has been liable to be affected by differences of temperature. Upon these intervals the effect of such changes of temperature as the apparatus is liable to be subjected to is not, I believe, of sensible amount with the scale of measurement adopted. Ordinarily, for the brighter portion of the spectrum, the width of the slit seldom exceeded $\frac{1}{400}$ inch; when this width had to be increased in consequence of the feebler illumination towards the ends of the spectrum, the measure of the nearest air-line as seen in the compound spectrum was again taken, and the places of the lines of the metal under observation were reckoned relatively to this known line.

By this method of frequent reference to the principal air-lines the measures are not sensibly affected by the errors which might have been introduced from the shifting of the lines in absolute position in consequence of alterations either in the width of the slit, in the place and direction of the discharge before the slit, or in the apparatus from variations of temperature, flexure, or other causes.

The usual place of the electrodes was about .7 inch from the slit, though occasionally they were brought nearer to the slit. When they are placed in such close proximity, the sparks charge the spectroscope by induction, but the inconvenience of sparks striking from the eyepiece to the observer may be prevented by placing the hand upon the apparatus, or putting the latter into metallic communication with the earth.

The spectrum of comparison was received by reflection from a prism placed in the usual manner over one-half of the slit. As the spectrum of the discharge between points of platinum, when these are not too close, is, with the exception of two or three easily recognised lines, a pure air-spectrum, this was usually employed as a convenient spectrum of comparison for distinguishing those lines in the compound spectrum which were due to the particular metal employed as electrodes. The measures, however, of all the lines, including those of the air-spectrum itself, were invariably taken from the light received into the instrument directly, and in no case has the position of a line been obtained by measures of it taken in the spectrum of the light reflected into the slit by the prism.

The measures of all the lines were taken more than once; and when any discordance was observed between the different sets, the lines were again observed. The spectra of most of the metals were re-measured at different times of observing. In the measurement of the solar lines for their co-ordination with the standard air-spectrum, the observations were repeated on several different occasions during the progress of the experiments. The line G of the solar Table is the one so marked by Kirchhoff.* When no change in the instrument could be detected, the measures came out very closely accordant—for the most part identical. The discordances due to small alterations in the instrument itself were never greater than 5 or 6 of the units of measurement in the whole arc of 4955 units. As the apparatus remained in one place, free from all apparent derangement, these alterations are probably due to changes of temperature. The method employed to eliminate these discordances has been described.

Throughout the whole of the bright portion of the spectrum the probable error of the measures of the narrow and well-defined lines does not, I believe, exceed one unit of the scale.

In the case of lines of sensible breadth and of nebulous bands, the point of intersection of the wires of the micrometer was brought as nearly as possible upon the centre of the lines.

7. It is well known that the lines of different metals as a whole, as well as the lines of the same metal amongst themselves, differ greatly in their characters. For example, the narrow, sharply defined lines of cobalt and iron contrast strikingly with the broader and nebulously edged lines of antimony and arsenic. The spectrum of zinc affords a good example of the differences in this respect between lines of the same metal. In general, it may be that, the less volatile a metal is, the narrower and more sharp are the lines—though indeed in the case of the metals barium, calcium, and strontium many of the lines are of hair-like narrowness and sharply defined.

* "Untersuchungen ü. d. Sonnenspectrum," 2 Theil, Taf. iii. Berlin, 1863.

In the spectra of many of the metals bands of light also exist, generally rather broad and faint, which are not resolvable with my instrument into lines. Many of these have the appearance of being true nebulous bands, whilst others under careful scrutiny present indications of being probably composed of lines.

These characteristic differences of the lines deserve more careful scrutiny than it was needful, in accordance with my present purpose, to bestow upon them. As approximative indications of their character, the following abbreviations are placed against the numbers in the tables :—

A line sharply defined at the edges, and narrow when the slit is narrow	s
A band of light, defined <i>as a line</i> , but remaining, even with a narrow slit, nebulous at the edges	n
A haze of light irresolvable into lines	h
Double, too close for measurement	d

The comparative intensity of the lines is indicated by the smaller figures, which are placed in the position of exponents against the numbers in the tables. I purposed to limit these estimations to the first ten figures, but so many faint lines were seen that the scale has been extended by adding fractional parts of unity. These figures may be accepted as approximative estimations of the relative intensity of the lines of *each* spectrum. But as the spectra were not, for this purpose, compared one with another, and so many circumstances affect eye-estimations of brightness, these figures must not be taken otherwise than as roughly indicating the values in relative intensity of the lines of *different* spectra.

In many cases some of the lines of one metal will be seen to be very closely approximated in position to those of another metal, though they do not actually coincide. In the tables there are lines of different metals having the same numbers; these may with a greater dispersive power be found to be only very near each other. In the case of some, there may be small errors of observation; for to have compared each spectrum with all the others would have involved very great labour.

8. I am indebted to the kindness of Professor W. A. Miller for the loan of specimens of gold, silver, thallium, cadmium, lead, tin, bismuth, antimony, arsenic, and palladium. Dr. Matthiessen has furnished me with lithium, calcium, and strontium* and purified tin, cadmium, lead, bismuth, antimony, and iron. I have procured from Messrs. Johnson and Matthey tellurium, palladium, osmium, rhodium, iridium, and pure platinum.

I have electro deposited upon platinum, from the solutions of their salts, silver, manganese, chromium, lead, tin, cadmium, cobalt, bismuth, nickel,

* Dr. Matthiessen informs me that "the calcium, strontium, and lithium were prepared from the pure chlorides as described in the *Quart. Journ. Chem. Soc.*, vol. viii., pp. 107, 143."

antimony, and iron. I have also prepared by the voltaic method amalgams of sodium, potassium, barium, and strontium.

9. *The Air-spectrum.*—The lines given in this spectrum are present with all electrodes when the spark is taken in air at the common pressure. To distinguish the lines which belong to air, the spectrum between electrodes of platinum was observed simultaneously with that between points of gold. The lines common to both these spectra were measured as those due to the components of air. The spectrum thus obtained remains invariably constant, with reference to the position and relative characteristics of its lines, with all the metals which have been employed. The air-spectrum *as a whole*, however, varies considerably in intensity and distinctness with electrodes of different metals. As the lines are due to the stratum of air separating the points of the electrodes, it is to be expected that these lines will appear strongest and most distinct when those metals are employed which, being less volatile, will therefore in a less degree displace the air between the electrodes with their own special vapour. This consideration appears to be confirmed by observation. The air-spectrum is especially intense and distinct when the spark is taken between points of platinum, gold, iridium, and rhodium; whilst, of all the metals which I have employed, mercury and sodium, perhaps, are those with which the intensity of the air-spectrum is most diminished. With these comparatively very volatile metals, the air between and about the electrodes must be, to a very considerable extent, replaced by the metals themselves in a state of vapour. It accords with this suggested explanation of the differences in brightness of the air-lines with different metals, that, if the electrodes be mercury or sodium and a platinum wire, the air-spectrum is observed to be weaker when the current is so directed that the greater heating effect of the discharge shall be at the mercury or sodium electrode, and to become perceptibly stronger when the current is reversed. It is known that, within certain limits, the air-spectrum is rendered more intense by the separation of the electrodes.

The following experiments have been made to refer the lines of this compound spectrum to the components of common air to which they severally belong:—

a. *Hydrogen.*—The strong line of the air-spectrum at 589·5 is coincident with Fraunhofer's C, and with the red line of hydrogen.

When the spark is taken in air that has passed over sulphuric acid, this line becomes very faint. A larger surface of acid being employed, the line faded out so completely that no trace of it could be perceived. Steam was then mixed with air, when this line became much brighter and the other lines of hydrogen appeared.

The presence and comparative brightness of this line form a delicate test

for aqueous vapour. [Lord Rayleigh has (1897-1902) made use of this delicate test for determining the question of hydrogen in the atmosphere. His experiments did not confirm A. Gautier's statement that the atmosphere contains as much as 2 parts in 10,000 of hydrogen. 1909.*]

b. *Carbonic Acid*.—Air that had passed through a solution of caustic potash was examined, but its spectrum was not observed to differ from that of ordinary air. When carbonic acid is added to air, several prominent lines make their appearance. These are due to carbon, since they coincide with lines in the spectrum of graphite. One of the strongest and most characteristic of these lines, and a test for carbonic acid, is a red line a little less refrangible than the hydrogen line. Its number is 580·5.

[Though a good indication of the oxygen and nitrogen compounds of carbon, the absence of this line must not always be accepted as a proof that no carbon is present. I have recently found that, when carbon is subjected to the induction spark in the presence of hydrogen, this line in the red is not seen. Further details of these experiments will be given when the spectrum of carbon is described.—February 7, 1864.]

c. *Nitrogen*.—In the spectrum of the electric spark when taken in a current of pure nitrogen, a few of the lines of common air are wanting, but no new lines appear. The lines of the air-spectrum which remain in nitrogen preserve unaltered their relative brightness and their distinctive characters. In the tables these lines are distinguished by the letter N.

The nitrogen was prepared by causing air freed from carbonic acid by potash to pass over red-hot finely divided copper which had been previously reduced from the oxide by hydrogen. The nitrogen was then dried by sulphuric acid. The freeness of the nitrogen from oxygen and from moisture was shown by the total extinction of all the lines which did not retain their usual brightness, and the absence of any trace of the strong hydrogen line. Subsequently a fresh portion of nitrogen was prepared by the same method, and a portion of it sealed up at the common pressure in a glass tube of suitable form, pierced with platinum electrodes. This tube continues to give results identical with those obtained in the current of nitrogen.

d. *Oxygen*.—When a current of oxygen from fused chlorate of potash was substituted for nitrogen, the numerous lines of the nitrogen spectrum faded out, and those which were extinguished by nitrogen reappeared with an intensity greater than they possess when the spark passes in air. These are distinguished in the tables with the letter O.

No new lines were added to the spectrum, but an unexpected result was observed. Two (it may be, three) of the lines visible in nitrogen remained also in oxygen. The most noticeable of these is the double line 2642. This

* *Phil. Mag.*, 1901, Part I., p. 100, and 1902, p. 416.

in the air-spectrum is not quite so strong as the line next in greater refrangibility. This brighter line became extinct in oxygen at the same time that the double line remained fully as brilliant as in air, if not a little exalted in intensity. This result, therefore, could not be due to any oxygen remaining in the nitrogen, or of nitrogen in the oxygen. The other line, which behaves similarly in oxygen and nitrogen, is the hazy one in the red, 807. The line in the tables marked with the symbols of nitrogen and oxygen, at 3456, is in the air-spectrum a double line. The narrow defined line of nitrogen is superposed upon the broader nebulous line of oxygen. Oxygen and nitrogen from other sources were then examined. Nitrogen was evolved from a mixture of nitrite of potash and chloride of ammonium. Oxygen was obtained from peroxide of manganese and sulphuric acid, also from bichromate of potash and sulphuric acid, and also from oxide of mercury. The gases thus prepared were identical in their action upon the spectrum with those previously examined. I have not at present carried this inquiry further.

[I have carefully re-examined the lines which are apparently common to nitrogen and to oxygen. I now regard them as due to the superposition in the air-spectrum of lines of oxygen and of nitrogen. When the most remarkable of these, the double line 2642, is closely observed with the eyepiece of a power of 35 times, the double line, as a whole, appears to become in a slight degree more refrangible when the air is replaced by oxygen. As the oxygen lines of the air-spectrum become more brilliant in oxygen, the phenomenon observed may be explained by supposing a pair of unequally bright oxygen lines to be closely approximated in position to, but a little more refrangible than, a similar pair of nitrogen lines.

In air these four lines would form an ill-defined double line, while in oxygen the exaltation in brilliancy of the lines due to oxygen would make up for the extinction of those of nitrogen, thus leaving a pair similar to that seen in air, but now a little more refrangible, from the loss of the less refrangible line of nitrogen, and the greater brightness of the faint and more refrangible of the oxygen lines. This explanation exactly corresponds with the changes in appearance and position of the double line. The observations have been repeated several times with oxygen from chlorate of potash, and also with oxygen from bichromate of potash and sulphuric acid. The change in position as observed relatively to the corresponding air-line in the spectrum of comparison was not relied upon. The fixed cross of the micrometer was made to coincide with the oxygen line next in less refrangibility, 2626; the movable cross was then brought upon the centre of the brighter of the pair 2642. When a current of pure oxygen was made to pass through the glass tube in which the platinum electrodes were sealed, the double line was seen to have moved from the point of intersection of the wires toward the more refrangible end of the

spectrum. To restore the cross to a position similar to that which it before occupied—namely, upon the centre nearly of the brighter of the pair of lines—required that the screw should be turned through a part of a revolution corresponding to a little more than two units of the scale. This measure is greater than the *apparent* change in position would have suggested, for in oxygen the lines are rather broader and more nebulous. The distance between the components of the double line is greater in oxygen. The alterations of position and of character are much better seen when the spectra of oxygen and nitrogen are viewed simultaneously.

A similar explanation is to be given of the nebulous band in the red at 807. In oxygen the position of greatest brightness is more refrangible than it is in air and in nitrogen, though the band itself does not advance beyond the more refrangible limit of the corresponding band in air. The line at 629·5 is a pure nitrogen one, and fades out completely in oxygen, but then a nebulous line appears at a little distance, about 638. Of this, in the air-spectrum, a faint trace only can be perceived.—February, 1864.]

10. *Sodium*.—When the spark was passed between electrodes of sodium, in addition to the well-known double line, three other pairs of lines and a nebulous band made their appearance in the spectrum. The two more prominent of these are not far from air-lines, and with an instrument of insufficient dispersive power might easily be confounded with them. As these lines might be occasioned by impurities in the commercial sodium employed, I prepared an amalgam of sodium, by making mercury the negative electrode in a solution of pure chloride of sodium. The mercury had been examined, and its spectrum was known. When the spark passed between this amalgam and a platinum wire, the same lines were seen, with their peculiar characteristics of relative position and intensity. Cotton moistened with solutions of chloride of sodium and of nitrate of soda was then used as one electrode, the other being a platinum wire. With both these salts the pairs at 820 and 1170 were satisfactorily observed, though it was with some difficulty, and only by occasional glimpses.

I then compared the sodium-spectrum directly with that of the sun. So numerous are the fine lines of the solar spectrum, and so difficult is it to be certain of absolute coincidence, that I hesitate to say more than that the pair of lines 818 and 821 appeared to agree in position with Kirchhoff's lines 864·4 and 867·1; and of the pair 1169 and 1174, one appears to coincide with a line sharply seen in the solar spectrum, but not marked in Kirchhoff's map, which would be about 1150·2 of his scale, and the other with Kirchhoff's line 1154·2. The other pair and the nebulous band are too faint to admit of satisfactory comparison with solar lines.

11. *Potassium*.—When commercial potassium is employed as an electrode,

about sixteen lines are seen in addition to the pair near A of the solar spectrum. Four quite distinct specimens of potassium gave identical results, the same lines being visible in all, and no other lines. I then prepared by electricity an amalgam of potassium, but, with the exception of the line 840 occasionally visible, the lines were not seen. As the potassium lines are fainter than those of sodium, this negative result does not appear to be conclusive, since the great intensity of the mercury-spectrum might overpower the feebler lines of potassium, especially when this was present only in small quantity and not in the concentrated metallic form. One electrode was then surrounded with cotton containing concentrated solution of chloride of potassium, and afterwards with cotton containing that of caustic potash. With both these, rather more easily with the latter, the lines 840, 1049, 1065, and 1073 were occasionally and faintly perceived.

[This great diminution in the brilliancy and number of the lines when, in the place of metallic potassium, solutions of its salts are substituted, may be due to the unfavourable condition of the latter for the production of potassium vapour. The large volume of the gases formed by the decomposition of the water must disperse and attenuate the comparatively small volume of vapour of the element forming the base of the salt, and also the great expansion in the gaseous state of the constituents of the water would lower the temperature of the vapour of potassium mingled with them. The salts should be subjected to the discharge free from water, and in a condition in which they conduct the current. If dry, or fused upon the wires, they are disrupted and scattered.

A platinum wire was coiled at one extremity into a little cup-like cage. Chloride of potassium was placed in this and fused.* This wire, with the fused bead of chloride, was placed *above* the platinum wire forming the other electrode. A spirit-lamp is placed beneath the wires; as soon as the bead is in a state of fusion, the lamp is withdrawn and contact immediately made. During the few seconds that the chloride remains fused, most of the lines of metallic potassium are seen. Of the lines 1328 and 840 the observation is less certain, and is very doubtful of 763 and of 727.[†]

Protochloride of tin similarly employed gives a brilliant spectrum of tin.—
February 1864.]

12. *Calcium*.—The spectrum was obtained from electrodes of metallic calcium, supplied to me by Dr. Matthiessen. The colour of the spark, as seen by the eye, is brilliant red purple. The contrast is exceedingly beautiful

* The method of fused chlorides has been since successfully employed by De Gramont and others.

[†] "Il y a encore dans le rouge trois raies bien nettes, 6308·0, 6245·5, et 6117·5, qui, entrevues aet données par Huggins, n'avaient pas été revues par les observateurs suivants, qui les avaient tribuées à des impuretés."—De Gramont, *Comptes rendus*, 15 Juin, 1896.

between this and the intense green light of thallium. Two or three nebulous bands in the red present indications of resolvability. There is also a diffused green light from 1297 to 1375. The line 1506 is in a small degree more refrangible than the strong thallium line. The strong line 1260 is very near a tin line, but the contrast between the sharp calcium line and the nebulous tin line is very marked. A pair of strong lines is seen near the extreme refrangible end of the spectrum, which may coincide with those of Fraunhofer's H. This specimen of calcium produced also the lines of magnesium; these were of course omitted, as on the chemical analysis of this specimen of calcium it was found to contain magnesium.

13. *Barium*.—As I could not obtain barium in the metallic state, I prepared an amalgam of barium by the electrolysis of chloride of barium. The mercury was a portion of the same used in the other experiments, and which had been examined in the spectroscope. The spectrum is one of great beauty, and the lines are for the most part sharp, narrow, and intense. There is a very strong line in the indigo, near a line of platinum; the latter is furnished also by my specimens of iridium and rhodium.

The line next in greater refrangibility appears to agree very nearly in position with one of tin.

14. *Strontium*.—Metallic strontium prepared by Dr. Matthiessen was employed. The spectrum is exceedingly brilliant, the lines being numerous, narrow, and intense. It is remarkable for several bright nebulous columns in the red and orange; these present indications of containing numerous fine lines.

This metallic strontium contains calcium, the lines of which have been eliminated. An amalgam of strontium was prepared, and with this all the principal lines of the spectrum from the metal were confirmed. As might be expected, many of the fainter lines were not recognised in the spectrum of the amalgam.

15. *Manganese*.—The lines were obtained from an electro-deposit of manganese from a solution of the chloride of manganese. Upon comparing this with a specimen of manganese which I was informed had been reduced by charcoal, all the lines of the electro-deposited manganese were seen in the other; but this contained, in addition, the numerous lines of the iron-spectrum. The most characteristic groups are a triple line from 909 to 915.5, the five lines from 2267 to 2401, and the close group extending from 3097 to 3133.

There are two remarkable broad nebulous bands, one at 840 and the other at 1565; the former, I suspect, is double. As the deposited manganese is brittle, the lines were fitful in consequence of the disruption of portions of the deposit by the spark. This may be the reason that some of the finer lines were not observed.

16. *Thallium*.—The specimen of thallium was lent me by Professor W. A. Miller, who received it as pure thallium from Mr. Crookes. With the exception of a few faint lines, one in the red rather strong, and a distinct line near the most refrangible end, the spectrum agreed with the description in Professor Miller's "Note on Thallium."*

17. *Silver*.—The spectrum is that of electrotype silver, obtained from pure nitrate of silver in cyanide of potassium.

18. *Tellurium*.—This metal was supplied to me as pure by Messrs. Johnson and Matthey. It contains many strong and characteristic lines. The strong line in the red is very near the strong line in cadmium, but the latter is in a small degree less refrangible.

19. *Tin*.—The spectrum was obtained from purified tin, and confirmed by comparison with electrotype tin; one line, not observed in the spectrum of the latter, has been omitted.

20. *Iron*.—Electrotype iron was employed. The spectrum agreed exactly with a specimen received from Dr. Matthiessen as very nearly, if not quite, pure iron.

21. *Cadmium*.—The spectrum of purified cadmium was confirmed by comparison with cadmium electro-deposited.

22. *Antimony*.—The numerous and strong lines of this spectrum are, for the most part, nebulous at their boundaries. The spectrum is that of electro-deposited antimony.

23. *Gold*.—The specimen of which the spectrum is given was received from Professor Miller. It was reduced by him from the pure chloride, and fused under bisulphate of potash.

24. *Bismuth*.—Electro-deposited from the nitrate of bismuth.

25. *Mercury*.—Commercially pure mercury was washed with nitric acid, and then distilled. A portion of this was placed in a small cup made from glass tube, into which a platinum wire was sealed. The other electrode was a platinum wire.

26. *Cobalt*.—Electrotype cobalt from the chloride was employed. The lines are numerous, sharp, and narrow, and in the groupings there is considerable resemblance to the spectrum of iron.

27. *Arsenic*.—From a specimen of carefully re-sublimed arsenic received from Professor Miller. The strong line 1814 is very near, but not quite so refrangible as, one of the strong lines of copper. The strong line in the red, 812, is near the hazy band of the air-spectrum.

28. *Lead*.—The lead was obtained by electrolysis from the nitrate of lead.

29. *Zinc*.—Electrotype zinc was used. This spectrum is remarkable for the strong contrast between the nebulous lines, and others near them sharply defined.

* *Proc. Roy. Soc.*, January 1863, vol. xii., p. 407.

30. *Chromium*.—The chromium was electro-deposited. The triple nebulous band from 1081 to 1090 is remarkable. The groups of lines in the blue and indigo, which for the most part fall between air-lines, are very beautiful, and in a marked manner characteristic of this metal.

31. *Osmium*.—Received as pure from Messrs. Johnson and Matthey. Iridium and rhodium have also been measured, but, as these have lines in common, their spectra are deferred.

32. *Palladium*.—A specimen prepared by Dr. Wollaston was observed simultaneously with palladium received as pure from Messrs. Johnson and Matthey. The latter contained several lines which were not in the Wollaston specimen. The lines only which were common to both spectra were measured, and are given in the tables.

Nebulous bands, probably resolvable, are seen at 1000, and from 1219 to 1233.

33. *Platinum*.—The lines of platinum are not easily observed, as several of them are fainter than the air-lines near which they occur. The points of platinum must be brought near each other. The spectrum was mapped from electrodes of platinum wire specially prepared by Messrs. Johnson and Matthey as "pure" platinum.

There are two bands of fine lines at 913 and 939.

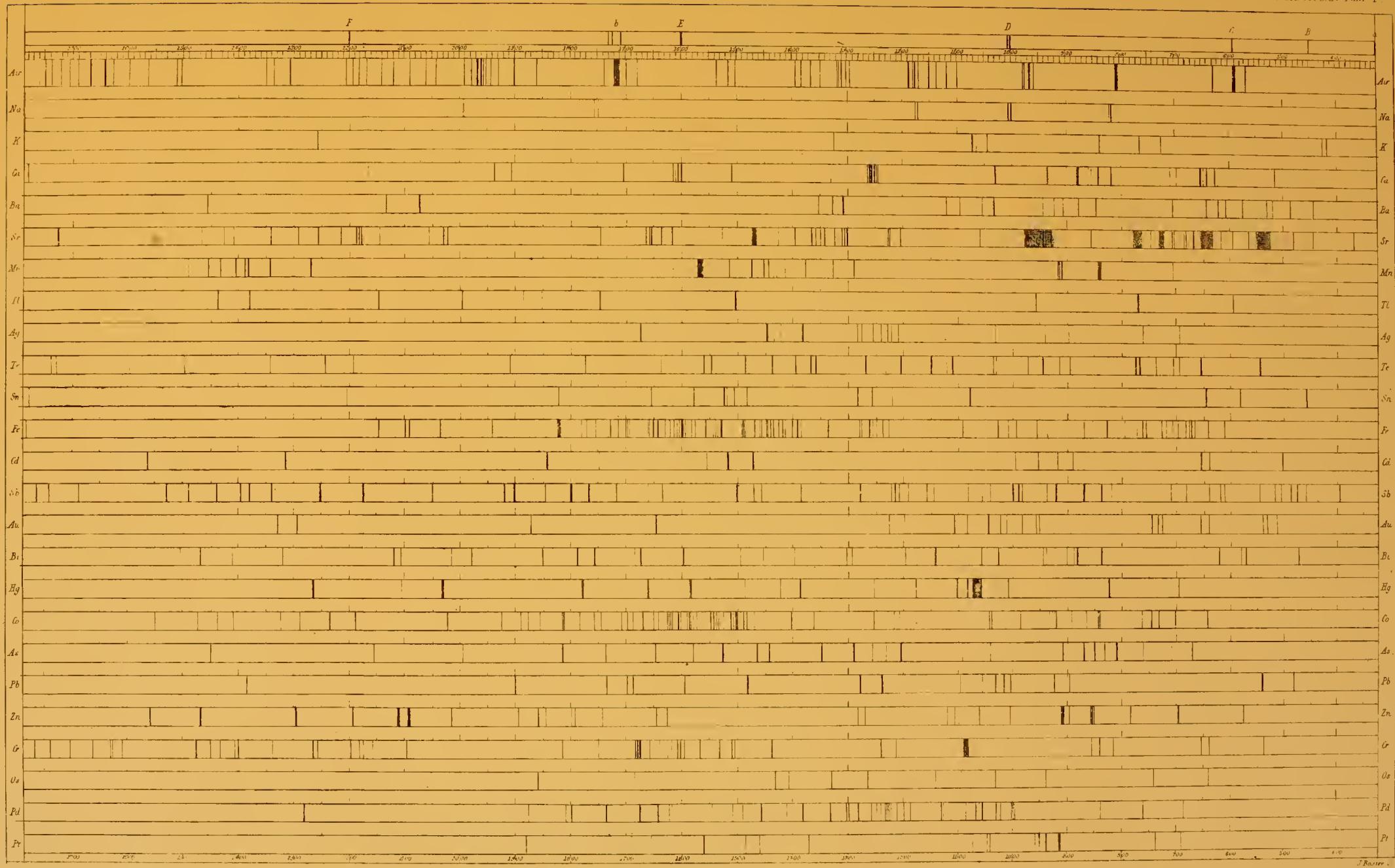
34. The spectrum of *Lithium* was observed from electrodes of metallic lithium. Only one line of moderate intensity was seen in addition to the three strong lines which are known. The numbers are 521⁵s, 856⁸s, 2013²s, 2732⁵n.

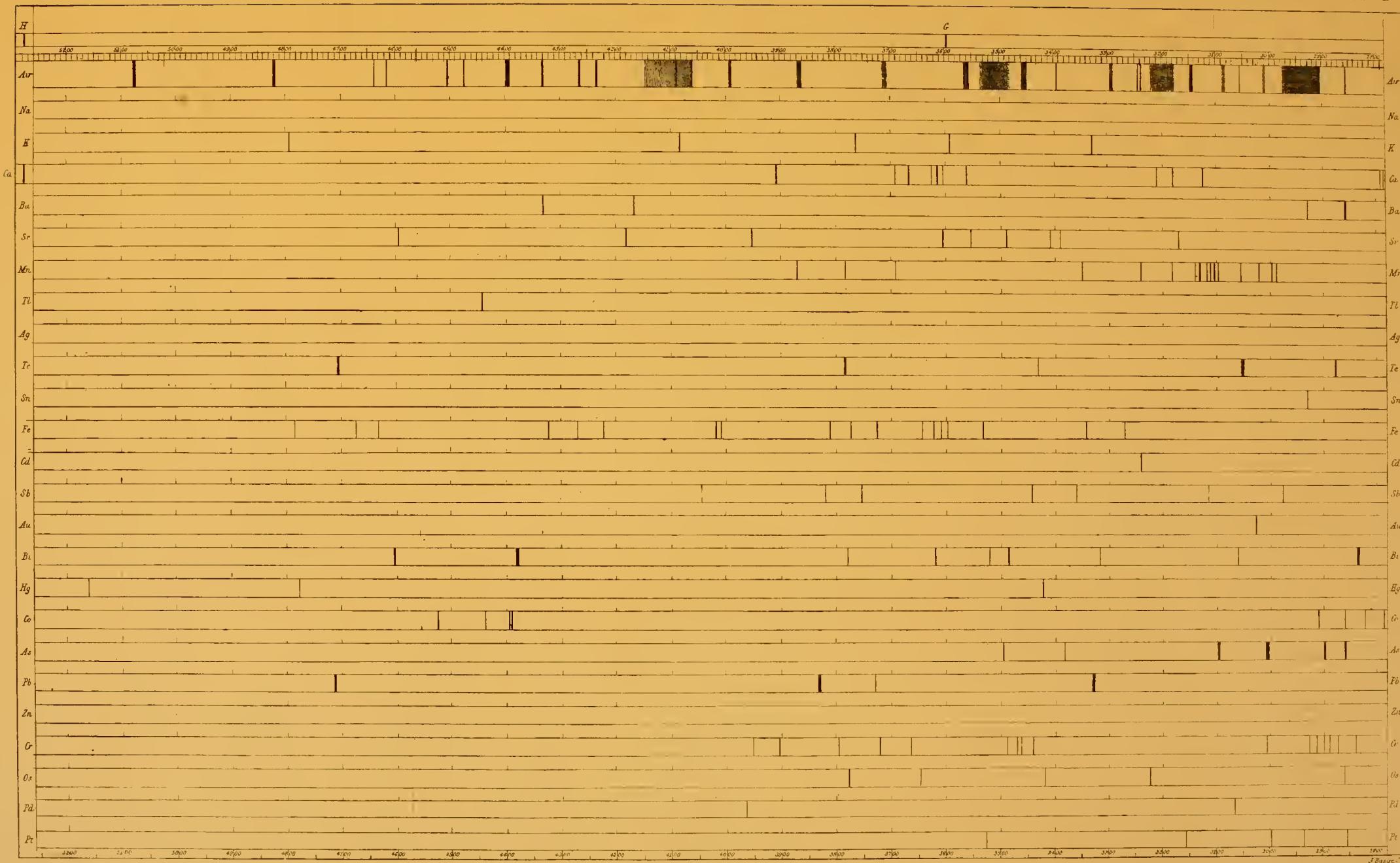
35. Several other spectra have been measured, or are in progress; these are reserved until the remaining metals and elements, as far as may be practicable, have been investigated.

NOTES TO PLATES I. AND II.

The scale upon which the spectra have been laid down limits the intensity that can be given, in the engraving, to the stronger lines. From this cause the spectra, as engraved, appear too faint. If greater force had been given to the lines, by making them broader, they would, in several spectra, have occupied singly the space in which two or more lines have to be laid down. This deficiency in strength of some of the lines is more appreciated by the eye, in consequence of the shortness of the lines of the spectra, with the exception of those of the air-spectrum. The narrowness of the spectra of the metals is unavoidable, if the great advantage of having all the spectra upon one Plate is retained.

In some of the spectra bands of unresolved light occur; these, in the Plates, are crossed with lines that they may be distinguished from groups of fine lines.





NOTE TO THE TABLES

Upon a re-examination of the tables I found that it frequently occurs that lines of two or more metals were denoted by the same number. It appeared probable that these lines having a common number were not coincident, but only approximated in position within the limits of one unit of the scale employed; and besides, there might be small errors of observation. I therefore selected about fifty of these groups of lines denoted by common numbers, and compared the lines of each group the one with the other, by a simultaneous observation of the different metals to which they belong. Some of the lines were found to be too faint and ill-defined to admit of being more accurately determined in position relatively to each other.

(For a reduction of these measures to wave-lengths, see Walcott Gibbs, *Amer. Journ. Sci. and Arts*, vol. xlvi., March, 1869.)

The following lines appear with my instrument to be coincident :

Zn, As 909	Na, Ba 1005	O, As 1737
Na, Pb 1000	Te, N 1366	Cr, N 2336

Of a much larger number of groups, the lines were, by careful scrutiny, observed to differ in position by very small quantities, corresponding for the most part to fractional parts of the unit of measurement adopted in the tables. These are—

Sn 459	Ba 621·5	Te 657	Bi 837·3	Co 937	Sb 1081	Te 1485	Zn 1797
Sb 458·8	Bi 621	Cd 656	Sb 837	Sb 937·5	Au 1081·5	Fe 1485·3	Pd 1798
Ca 515	Ca 622	Fe 696·2	Cd 889	Au 981	Ca 1256	Tl 1505	Tl 1851
Au 516	Fe 623	Zn 696	Sb 889·5	Sb 981·5	Co 1257	Mn 1505·5	Bi 1851·3
Te 545·5	Au 643	Sb 765	As 908·8	Ca 1031	Fe 1276	Pd 1548	Sb 1900
Sb 545	Ca 642	Te 765·3	Mn 909	Pd 1031·5	Ag 1276·3	Fe 1548·2	Pb 1900·3
		Fe 641·5		Ag 1031·2			N 1900
				Pb 1031·1			
Sn 581	Ca 649	Na 818·3	Ca 921·2	Te 1030·3	Fe 1438	Pb 1593·3	
Bi 581·5	Sn 648	Ca 818	Tl 921		Te 1438·3	Fe 1593	
			Co 921				
			Sb 921·1				

TABLE I.

Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Te.	Sn.	Fe.
<i>a</i> 322						365 ² s						
B 449	418 ² s 426 ² s	441 ⁷ s 486 ⁷ s	444 ² s 480 ² s	459 ³ s	
										491 ¹ s	
C 589 ⁵	N 565 ⁵ ²	515 ⁷ s 532 ⁷ s	523 ⁷ s 549 ⁵ s	545 ³ ⁴ n	
H 589 ⁵ h	563 ¹ s 573 ¹ s	581 ¹ s	
	N 629 ⁵ ²	622 ⁵ s 625 ¹ ⁵ s 637 ⁷ s	621 ⁵ s 681 ¹ s	619 ² s 669 ⁴ s	623 ¹ s	
					642 ² s 649 ⁷ s	645 ¹ s 681 ¹ s	648 ⁷ s	667 ⁵ s	
					727 ⁵ s 763 ⁵ s	655 ³ s 699 ² s 709 ² s 723 ² s	681 ¹ s 684 ¹ s 692 ⁵ s 703 ² s	657 ³ ⁷ s	
						704 ² s	690 ² s	693 ¹ s	673 ¹ s	674 ⁵ n	
						705 ⁵ ⁶ s	703 ⁵ s	703 ⁵ n	683 ⁵ s	696 ² ⁵ s	
						723 ¹ s 745 ² s	723 ¹ h 745 ² s	723 ¹ h 745 ² s	726 ⁵ s	719 ⁵ s	
						760 ¹ h	760 ¹ h	762 ² s	765 ³ ³ n	758 ⁵ s	763 ⁵ s	
						777 ¹ h	777 ¹ h	768 ¹ h	774 ³ s	774 ³ s	772 ¹ s	
						807 ⁵ s	807 ⁵ s	837 ¹ h	795 ¹ s	
						843 ³ s 818 ¹ ⁵ s 821 ¹ s	847 ² s 879 ² s 859 ² s	843 ¹ s	829 ² s	
						863 ² s	852 ⁵ s	
						840 ¹ ⁵ s	894 ² s	869 ⁵ ⁵ s	
						882 ¹ h	882 ¹ h	909 ⁵ s	909 ⁵ s	
						921 ² ² s	921 ² ² s	917 ¹ s	937 ⁵ s	
						908 ¹ ⁵ s	909 ³ ⁵ s	899 ⁵ s	927 ⁵ n	927 ⁵ n	953 ⁵ s	
						934 ¹ h	925 ¹ ⁵ s 943 ¹ ⁵ s	924 ¹ h 941 ¹ h	913 ² ⁵ s 915 ² ⁵ s	913 ² ⁵ s 921 ² s	945 ³ ⁶ s	
						993 ⁵ s	945 ³ s	960 ⁶ s	943 ⁵ s	945 ³ ⁶ s	995 ² s	
D ¹ 1000	1000 ⁸ s	
D ² 1005	1005 ⁸ s	1005 ¹ n	
Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Te.	Sn.	Fe.

From *a* to D

Cd.	Sb.	Au.	Bi.	Hg.	Co.	As.	Pb.	Zn.	Cr.	Os.	Pd.	Pt.			
	396 ³	n													
....	458·5 ¹	n													
502 ⁴	s	475 ³	s	473 ⁴	s	480 ³	s					
....	487 ³	s							
....	501 ⁵	n													
....	516·5	s												
....	517 ¹	s	542·5 ⁷	s						
....	535·5	s												
....	545 ¹	n	541·5	s	572 ³	s	541 ¹	s				
....	614 ¹	n	581·5 ¹	h	577·5	n					
....	620 ¹	n													
639 ²	n	621 ⁴	s	645 ¹	n, d	621·5	n			
....	640 ¹	n	643·5	s	696 ⁷	s	640·5	n			
656 ⁸	s	643·5	s	641 ¹	s				
....	672 ¹	n							
....	654 ¹	n				
....	679 ²	h	685 ¹	n	701·5	s						
....	707 ¹	n	685·5	s			
....	697 ¹	n	731·2	s	689·5	s		
....	759 ¹	n					
....	719 ¹	n	745·5	s	782 ¹	s	741·7	s		
....	729 ²	n	727·5	s	762·2	s		
....	739 ²	n	734·5	s	763 ²	s				
....	765 ³	n	812 ⁶	n	898 ¹	s	817 ¹	n			
....	747 ³	s	826 ⁷	n	844 ¹	h	833 ¹	n	855 ⁵	n			
....	787 ¹	h	837·3 ⁵	n	850 ³	n	843 ^{1·5}	n			
....	796·5	h	884·5	n	863 ²	n	865 ⁷	s					
....	819 ²	n	891 ⁷	s	870 ²	n	856 ⁷	n			
889·5 ⁵	n	837 ⁷	n	887·5	s	895 ¹	s				
918 ¹	n	871 ⁷	n												
953 ¹	s	889 ³	n	899 ¹	s	908·8 ³	n	913	h	
986 ¹	s	921·1 ⁸	n	951·5	s	939 ¹	h	921 ¹	s	924 ²	n		
....	937·5 ²	n	956·5	s	943 ¹	h	923 ²	s	929·7	s	
....	981·5 ¹	n	981·7	s	931 ⁵	s	939	h
....	988·5 ³	n	937 ⁵	s	950·5	s
....	985 ²	s	958·5	s
....	1000·5 ³	n	1000 ¹	n	1001 ²	s	995	h	
												1005	h		
Cd.	Sb.	Au.	Bi.	Hg.	Co.	As.	Pb.	Zn.	Cr.	Os.	Pd.	Pt.			

TABLE II.

Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Ts.	Sn.	Fe.
D ² 1005			1031 ³⁻⁵ s	1011 ² s
			1049 ¹ n	1034 ⁶ s	1055 ² s	1031 ²⁻² s 1030 ³⁻⁵ s	1030 ² s
			1065 ⁵ n	1057 ¹ s	1061 ⁵ s
			1073 ¹⁻⁵ n	1096 ¹ s	1090 ⁵ s
N 1100 ⁻⁵	1099 ⁵ n	1076 ¹⁰ n
N 1118 ¹	1102 ⁵ n
N 1135 ⁻²	1169 ² s	1119 ¹ s	1122 ¹ s
N 1150 ²	1174 ¹ s
N 1171 ¹	1151 ⁷ n
N 1177 ⁸
N 1180 ¹
N 1187 ⁷	1225 ⁵ s
											
N 1294 ⁻⁵	1203 ¹ n	1207 ⁵ n	1247 ⁻⁵ s
N 1302 ⁻⁵	1247 ⁻⁵ s	1219 ² s	1251 ⁻² s
N 1310 ¹⁻⁵	1249 ⁻⁵ s	1227 ¹⁻⁵ s, t	1223 ⁻² n	1261 ² s
N 1314 ¹⁻⁵	1252 ¹⁻⁵ s	1227 ⁻⁷ n	1230 ¹ s	1274 ⁻⁷ s
N 1319 ⁻²	1256 ²⁻⁵ s	1240 ⁻³ s	1260 ⁸ n	1276 ⁻² s
N 1349 ¹⁻²	1258 ⁵⁻⁵ s	1268 ⁻² s	1289 ¹ s	1257 ⁻⁷ s	1270 ⁴ s	1338 ⁻⁷ s,d
			1260 ⁻⁴ s	1276 ⁻³ s	1383 ⁻⁵ s
N 1366 ¹	1265 ⁻⁷ s	1391 ⁻⁷ s
			1328 ¹ n	1271 ¹ s	1286 ⁻⁵ s	1284 ⁸ n	1400 ⁻⁷ s
N 1383 ⁻⁵	1413 ⁻⁵ s
N 1394 ⁻⁷	1307 ¹ s	1301 ² s	1419 ⁻⁷ s
			1335 ⁻⁷ s	1305 ²⁻⁵ s	1329 ¹⁻⁵ n	1421 ⁻⁵ s
					1311 ³ s	1434 ⁻⁵ s
					1324 ³ s	1438 ⁻⁵ s
					1351 ⁻⁵ s	1445 ⁻⁷ s
					1341 ³ s	1446 ⁻⁷ s
					1349 ⁻⁷ h	1456 ⁻⁷ s
					1359 ³ s	1350 ¹ s	1357 ⁴ s	1459 ⁵⁻² s
					1365 ⁴ s	1376 ¹ s	1372 ² s	1366 ⁴ s	1467 ⁻⁷ s
					1397 ²⁻⁵ s	1413 ⁻⁷ s	1380 ⁷ s	1396 ⁴ s	1481 ¹ s,d
					1428 ¹ s	1421 ⁻³ s	1485 ⁻³ s
					1425 ⁻² s	1438 ⁻⁷ s	1435 ⁻³ s	1438 ⁻³ s	1686 ⁻² s
					1467 ¹⁻⁵ h	1443 ⁻⁷ s	1446 ^{-h}	1484 ¹ s	1486 ⁻⁵ s
N 1502 ⁻²	1506 ¹ s	1452 ² s	1488 ⁻² s
N 1516 ⁻²	1456 ⁻² s	1532 ² s
					1473 ⁵⁻³ s	1485 ⁴ s	1537 ⁻⁷ s
N 1537 ⁻²	1505 ⁵⁻⁵ s	1505 ⁹ s	1506 ² n	1541 ⁻⁵ s
					1515 ⁴ s	1548 ⁻² s	1520 ¹ h	1545 ⁻⁵ s
						1559 ¹ h	1562 ² s	1576 ¹ n	1574 ⁻² s
E { 1599	1599 ⁵⁻⁴ s	1582 ⁻⁷ s,d
{ 1600	1593 ⁻⁵ s
												1599 ⁻⁷ s
												1600 ⁻⁷ s
Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Te.	Sn.	Fe.

From D to E.

Cd.	Sb.	Au.	Bi.	Hg.	Co.	As.	Pb.	Zn.	Cr.	Os.	Pd.	Pt.
....	1011 ¹ n	1008 ¹⁻⁵ n	1015 ³ n	1029 ¹ s	1023 ⁻³ s	
....	1025 ² s	1026 ² n	1019 ⁻⁵ n	1031 ⁻⁵ h	
....	1031 ¹⁻⁴ s	1041 ⁻⁵ s
....	1041 ⁻⁵ s	1045 ⁴ s	1059 ¹ n	1042 ¹ n	1045 ⁻⁵ s
....	1057 ⁻⁵ s	1060 ⁻³ n	
....	1056 ⁻⁷ s	
....	1081 ¹ n	1081 ⁻⁵ s	1074 h	1055 ⁻⁵ n	1081 ¹ h	1068 h
....	1145 ⁻⁵ n	1109 ¹ s	1083 ⁻⁵ n	1090 ⁻⁵ n	1094 ¹ n	1087 ¹ h	1073 ⁻⁷ d
....	1100 ⁻⁵ n	1110 ⁻⁵ s	1090 ¹ h	1093 ⁻⁵ s	1084 h
....	1143 ⁶ n	1122 ⁻⁵ n	
....	1158 ¹ n	1177 ² n	1141 ¹ s	1127 ⁻³ s	
....	1189 ⁻⁵ n	1197 ³ n	1129 ¹ s	
....	1185 ⁻⁵ s	
....	1203 ⁷ n	1212 ¹ s	
....	1207 ¹ h	
....	1214 ⁴ n	
....	1220 ¹ n	1252 ¹ n	1242 ¹⁻⁵ s	1199 ⁻⁵ s
....	1266 ⁻⁵ n	
....	1279 ⁴ n	
....	1293 ¹ s	1039 ⁻² s	1212 ⁻⁵ s	
....	1383 ³ n	1043 ⁻² s	
....	1305 ⁻⁵ s	1207 ⁻⁵ s	1231 ⁻⁵ n	1240 ⁹	
....	1217 ⁻⁵ s	1257 ⁻⁵ n	1264 ¹ s	1219 ¹ h
....	1257 ⁻⁷ s	1279 ⁵ n	1269 ⁻⁵ n	1233 ¹ h
....	1240 ⁻⁵ s
....	1283 ¹ n	1248 ⁻⁵ s
....	1361 ¹ s	1291 ⁶ n	1259 ⁻⁵ s,d
....	1401 ¹⁻⁵ s	
....	1470 ⁻⁵ s	1322 ² s	1281 ¹⁻⁵ s	
....	1483 ¹ s	1299 ¹ s	
....	1385 ¹⁰ n	1491 ¹ s	1348 ⁶ n	1301 ¹⁻⁵ n	
....	1496 ⁻² s	1331 ¹⁻⁵ n	1367 ⁻⁷ s
....	1395 ¹ h	1405 ⁻⁵ s	1380 ¹⁻⁵ s	
....	1500 ⁻⁵ s	
....	1421 ¹⁻⁵ n	1501 ⁻⁵ s	1439 ¹⁻⁵ s	1432 ¹⁻⁵ s	1412 ⁻⁵ s	
....	1473 ¹⁰ n	1471 ³ n	1453 ¹ h	1508 ⁻² s	1443 ¹ n	1456 ² s	1459 ⁻⁵ s
....	1487 ⁻⁵ n	1514 ¹ s	1507 ⁻⁵ s	1492 ⁻⁵ s	1484 ⁻⁵ s
....	1525 ⁻⁵ n,d	1465 ¹ n	1510 ¹ s	
....	1495 ¹ h	1534 ⁻⁵ s	1479 ⁷ n	1511 ⁻⁵ s	
....	1501	1539 ¹³ s	1548 ⁻⁵ s	
....	1517 ¹⁰ n	1543 ⁻² s	1532 ¹ s	1561 ² s
....	1549 ⁻⁵ s	1519 ⁻⁵ n	1569 ³ s	
....	1556 ¹ n	1573 ⁻² s	1529 ⁶ n	1567 ¹ s,d	
....	1579 ⁻² s	
....	1583 ⁻⁵ n	1584 ⁻² s	1577 ¹ n	1594 ⁻⁷ s	
....	1598 ⁷ n	1586 ¹⁻⁵ s	
....	1591 ⁻⁵ s	1593 ⁻³⁻⁵ n	

N.B. In the column Ba the line 1271⁴ should be 1308⁴, and the line 1307¹, 1327¹.

TABLE III.

Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Te.	Sn.	Fe.	
E $\left\{ \begin{array}{l} 1599 \\ 1600 \end{array} \right.$				1605 ³ s	1603 ⁵ s		
				1609 ⁵ s	1617 ³ s	1617 ⁵ s	1608 ⁵ s		
	O 1678 ⁵	1612 ¹⁻⁵ s	1638 ² s	1658 ⁵ n	1613 ³ s		
	O 1699 ⁵	1651 ⁵ s	1673 ⁵ n	1645 ¹ s	
b $\left\{ \begin{array}{l} 1708 \\ 1723 \\ 1731^5 \end{array} \right.$	N 1713 h	1702 ¹ s	1665 ¹ s	1653 ¹ s		
	N 1718 h*	1745 ¹ s	1747 ⁴ n	1662 ⁵ s,d	
	N 1721 h	1696 ³ s	
	O 1737 ³	1773 ¹ n	1698 ⁵ s	
		1746 ¹ n	1713 ⁷ s	
		1753 ⁵ n	1728 ¹ s	
	N 1860 ⁵	1817 ⁵	1851 ⁴ n	1767 ⁷ s	
	N 1900 ³	1907 ⁷ s	1885 ¹ s	1909 ⁵ n	
	N 1929 ⁷	
	N 1941 ⁵	1935 ³ s	
	N 1951 ⁵	
	N 1956 ⁵	1940 ¹ 5 s	
	N 1960 ⁵ ¹⁰	
	N 1967 ¹⁰	
	N 1978 ⁵	
	N 1990 ³	1991 h	1999 ² h	
	O 2043 ⁵	2021 ¹ s	2036 ¹⁻⁵ s	
	O 2060 ⁷	2029 ² s	
	N 2079 ⁵	2060 h	2146 ² s	
	O 2089 ⁵	2075 ⁹ n	2145 ¹ s	
	O 2119 ⁵	
	N 2140 ⁵	2176 ¹⁻⁵ s	2092 ¹ s	
	O 2145 ⁵	2133 ⁴ n	2098 ⁷ s,d	
	N 2168 ⁵	
				2172 ⁷ s	2147 ¹ s	
	O 2181 ⁵	2180 ¹⁻⁵ s	
	N 2192 ³	2185 ¹ s	2191 ¹ h	
F 2200													
Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Te.	Sn.	Fe	

* When the induction spark is taken in oxygen, a faint line is seen nearly in the position of the nitrogen line 1718. Since the lines of oxygen have a diminished intensity when the spark passes in air, this line would be too faint to be distinctly observed in the air-spectrum, in which it occurs in a position of close proximity to brighter lines of nitrogen.

From E to F.

Cd.	Sb.	Au.	Bi.	Hg.	Co.	As.	Pb.	Zn.	Cr.	Os.	Pd.	Pt.
.....	1602 ³ s	1605 ⁵ s
.....	1604 ³ s	1607 ¹ s	1617 ⁵ s
1636 ³ h	1617 ⁵ s	1648 ⁴ n	1619 ⁵ s	1622 ⁵ s
.....	1647 ⁵ s	1619 ³ s	1626 ¹ n	1626 ⁵ s	1642 ¹⁻⁵ s	1653 ¹ s
.....	1661 ¹ s	1662 ³ h	1622 ⁵ s	1640 ⁵ s	1674 ⁷ s
.....	1675 ¹⁰ n	1626 ³ s	1645 ⁵ n	1683 ⁵ s
.....	1685 ¹ n	1642 ⁵ s	1685 ¹ s	1657 ⁷ s
1715 ³ h	1650 ⁵ s	1677 ⁴ s
1747 ¹ s	1759 ⁷ n	1670 ¹⁻⁵ s	1737 ¹ n	1698 ¹ n	1680 ³ s	1689 ³ s
.....	1765 ³ h	1777 ⁵ h	1685 ⁵ s	1681 ⁵ s	1735 ² s
.....	1787 ⁶ n	1699 ⁵ s	1743 ⁵ n	1749 ² n
.....	1707 ⁵ s	1735 ⁵ n	1790 ⁵ n	1798 ¹⁻³ s
.....	1803 ³ h	1743 ⁵ s	1797 ⁵ n	1807 ¹ s
1843 ¹⁰ s	1834 ¹ n	1756 ⁵ s	1815 ⁷ n	1859 ⁵ s	1873 ⁵ s	1879 ¹ s
.....	1849 ¹ s	1851 ³⁻⁵ n	1813h	1814 ⁵ n	1845 ⁵ n	1859 ¹ n
.....	1869 ⁵ s	1859 ¹ n	1859 ⁵ s
.....	1857 ⁵ h	1890 ³⁻⁵ n	1893 ⁵ n	1873 ⁵ s	1879 ¹ s
.....	1900 ² h	1876 ³ s	1900 ³⁻⁵ n	1893 ⁵ n
.....	1887 ³ s
.....	1919 ² h	1925 ⁵ s
.....	1979 ¹ h
.....	2015 ¹ h	2021 ⁵ s	1993 ² n	2016 ⁵ n
.....	2033 ¹ h	2091 ⁸ n	2097 ¹ s
.....	2051 ³ n	2110 ⁸ n
.....	2101 ⁵ h	2110 ⁸ n
.....	2105 ⁵ n	2156 ¹ s	2175 ¹⁻⁵ s
.....	2119 ¹ n	2153 ¹ n	2175 ⁷ s
.....	2171 ³ n	2186 ³ s	2181 ³ s	2198 ⁵ s
.....	2191 ⁵ n	2198 ⁵ s

Scientific Papers

TABLE IV.

Solar.	Air.	Na.	K.	Ca.	Ba.	Sr.	Mn.	Tl.	Ag.	Te.	Sn.	Fe.
F 2200	N 2205 ⁵	2213 ¹ s						
	O 2213 ³											
	N 2221 ³											
	N 2305 ²	2254 ^{1.5} s	2267 ⁶ s	2245 ¹ h	2205 ³ n
	N 2336 ¹	2291 ^{1.7} s	2343 ⁵ s	2341 ⁵ h
	N 2350 ⁷	2260 ² n	2343 ^{1.5} s	2379 ⁶ s	2497 h
	O 2502 ⁷ n	2410 ⁵ s	2385 ⁵ s	2379 ² n
	O 2512 ⁷ n	2427 ¹ s	2401 ⁵ s	2595 ¹ n
	O 2563 ⁵ n	2459 ⁵ s	2469 ¹ s	2433 ¹ s	2437 ⁴ n	2613 ¹ n
	O 2597 ⁵ n	2726 ⁵ n	2456 ¹ s
	O 2626 ²	2492 h	2777 ² n	2781 ⁵ s
	N, O 2642 ² d	2535 ⁵ s	2730 ¹ n
	N 2669 ³	2739 ¹ n
	N 2689 ¹
	N 2707 ¹
	N 2722 ^{1.5}
	N 2738 ^{1.5}
	O 2748 ¹	2277 ⁵ s
	O 2766 ¹	2784 ³ n
	N 2856 h	2792 ² s	2856 ⁹ s
	N 2904 h	2875 h
	N 2978 h	2987 ⁷ s
	N 3009 ¹	2931 ³ n	2999 ⁷ s
	N 3011 ¹	3021 ¹ s	3272 ^{1.5} s
	N 3056 h
	O 3086 h	3054 ¹ s	2931 ⁴ n
	N 3144 d	3124 ³ s	3097 ¹ s	3051 ¹ h	3341 ² s
	N 3174 h	3181 ³ s	3169 ¹ s	3102 ² s	3532 ^{1.5} s
	N 3219 h	3114 ¹ s	3435 ⁵ n
	O 3238 ¹ n	3212 ² s	3120 ¹ s
	O 3241 ¹ n	3389 ⁵ n	3131 ^{5.3} s
	N 3292 h	3328 ² n	3561 ³ s	3409 ⁵ n	3133 ² s
	O 3395 ¹ n	3602 ^{5.2} s	3141 ¹ s
	O, N 3456 ² n	3617 ⁴ s	3489 ¹ n	3180 ¹ s
G 3597	O 3560 ¹ n,d	3591 ^{1.5} n	3628 ^{2.5} s	3553 ¹ h	3242 ¹ s	3597 ^{1.5} s
	O 3710 h	3665 ³ s	3604 ⁵ n	3691 ¹ s	3610 ^{1.5} s
	N 3863 h	3762 ² n	3692 ^{2.5} s	3749 ¹ s	3619 ² n	3623 ³ s
	N 3991 h	3952 ⁵ n	3782 ¹ s	3645 ^{.5} s
	O 4059 ¹	3909 ⁶ s	3728 ² s
	O 4087 ¹	4082 ³ n	4181 ³ n	3870 ⁸ s	3773 ^{1.5} s
	N 4145 h	4167 ² n	3779 h	3812 ^{1.5} s
	O 4232
	N 4263 ¹ n	4009 ¹ s
	N 4330 h	4332 ⁵ n	4019 ¹ s
H 5277	O 4395 ²	4221 ¹ s
	N 4473 ¹ n	4443 ³ n	4267 ¹ s
	N 4505 ¹ n	4703 ³ h	4323 ¹ s
	O 4615 ¹ n	4599 ³ n	4633 ¹ s
	O 4639 ¹ n	4791 ³ n	4671 ¹ s
H 5277	N 4821 h	4781 ¹ s
	N 5077 ⁷	5277 ⁶ n
Solar.	Air.	Na.	K.	Ca.	Ba.	St.	Mn.	Tl.	Ag.	Te.	Sn.	Fe.

Chemical Spectra

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From F to H.

Cd.	Sb.	An.	Bi.	Hg.	Co.	As.	Pb.	Zn.	Cr.	Os.	Pd.	Pt.
Cb.	Sb.	Au.	Bi.	Hg.	Co.	A.	Pb.	Zn.	Cr.	Os.	Pd.	Pt.
.....	2251 ² n	2257 ⁵ s
2315 ⁸ s	2339 ² h	2266 ^{1.5} s	2279 ^{.5^2} s
.....	2377 ² h	2291 ^{.5} s	2236 ³ s
.....	2397 ² n	2263 ^{.5} n	2294 ¹ s	2336 ^{.7} s
2562 ⁶ s	2440 ² n	2326 ⁴ s	2317 ¹ n	2286 ² s	2384 ³ n
.....	2488 ³ n	2325 ¹ s	2384 ³ n	2400 ¹ s
.....	2408 ¹ n	2409 ^{.5} s	2406 ^{.5} s
.....	2529 ³ n	2467 ⁵ n	2438 ^{.5} s	2450 ¹ n	2435 ^{.7} s
.....	2687 ¹ h	2453 ¹ n	2471 ^{.5} s	2469 ⁶ s	2452 ^{.7} s
.....	2740 ¹ h	2502 ¹ n	2550 ^{.5} s	2474 ¹ s
.....	2763 ² n
.....	2785 ² n	2559 ⁴ s
.....	2619 ¹ s
.....	2837 ⁵ n	2627 ^{.7} s
.....	2977 ² n	2823 ¹ n	2859 ¹ h	2632 ^{1.5} s, d	2857 ¹ s
.....	3060 ¹ n	2897 ¹ h	2663 ^{.5} s	2936 ^{.5} s
.....	2862 ¹ s	2701 ^{.7} s
.....
.....	3026 ^{2.5} s	2910 ³ s	2740 ^{.7} s	2999 ^{.7} s
3239 ⁴ s	3115 ¹ n	2768 ^{.7} s	3065 ^{.7} s
.....	3006 ^{1.5} h	2840 ^{.7} s	2861 ^{.7} s
.....	3359 ¹ h	2871 ^{.7} s	3156 ¹ s
.....	3315 ² n	3097 ^{2.5} h	2887 ^{.7} s	3225 ² s
.....	3446 ⁴ n	3481 ³ n	3421 ⁸ n	2899 ^{.7} s	3421 ¹ s
.....	3329 ⁷ n	2914 ¹ s
.....	3519 ² n	2927 ¹ s	3583 ¹ s	3525 ¹ s
.....	3756 ³ n	3381 ¹ n	3007 ¹ s
.....	3819 ¹ n	3619 ⁵ n	3444 ² s	3645 ¹ s
.....	4043 ^{1.5} n	3497 ¹ n	3730 ² n	3465 ¹ s
.....	3778 ⁵ n	3831 ⁶ n	3473 ¹ s	3719 ³ s	3963 ⁴ s
.....	3489 ¹ s	3905 ¹ s
.....	3663 ³ s	3773 ³ s
.....	4378 ⁴ n	4775 ⁴ n	4388 ³ n	3719 ³ s
.....	4603 ³ n	4437 ¹ n	4394 ³ n	3797 ³ s	3963 ⁴ s
.....	5158 ³ n	4523 ¹ n	4713 ⁷ n	3951 ¹ n

SPECTRA OF ERBIA AND SOME OTHER EARTHS

(From *Proc. Roy. Soc.*, vol. xviii., p. 546, 1870)

BAHR and Bunsen have shown * that erbia, rendered incandescent in a Bunsen's gas-flame, gives a spectrum of bright lines in addition to a brilliant continuous spectrum. As they were unable to discover the bright lines in the flame beyond the limits of the solid erbia, they suggest that the light which is dispersed by the prism into bright lines is emitted by the solid erbia, which substance therefore appears to stand alone, as a remarkable exception, among solid bodies. Bahr and Bunsen found the spectrum of bright lines to coincide very nearly with the absorption spectrum of some compounds of erbium.

A few weeks since, when in Ireland, I made the observation that the spectrum of the ordinary lime-light contains bright lines.† Dr. Emerson Reynolds, Director of the Laboratory of the Royal Dublin Society, kindly undertook to make experiments to ascertain from the position of the lines if they were due to the cylinder of lime, or to impurities contained in it.

Upon my return to town I made the following experiments; shortly after commencing them I received from Dr. Reynolds the account of his experiments, which, with his permission, I have added to this note.

Erbia.—A few months since I received, through the kindness of Dr. Roscoe, F.R.S., a few grains of nitrate of erbia, which he had procured from a trustworthy source. I followed Bunsen's method of placing it with syrupy phosphoric acid upon a platinum wire. The erbia, obtained by this method in a finely divided state, was then submitted to the heat of the oxyhydrogen blowpipe.

In all the experiments described in this paper hydrogen alone was first turned on, and the effect of the heat of the flame on the substance under examination observed with the spectroscope. Oxygen was then admitted slowly, and the effect of the increased heat carefully noted.

With the flame of hydrogen alone, the lines represented in the map which accompanies Bahr and Bunsen's paper were seen, but the lines were more distinct when a small proportion of oxygen was admitted. With the full proportion of oxygen, the light from the glowing erbia was more intense, but the lines were not so well seen. Even with the intense heat of the oxyhydrogen flame I was unable to trace the lines beyond the limits of the solid erbia, though the line of sodium could be seen for some distance from the erbia. I found, however, that the lines appeared more distinct, in consequence, probably, of

* *Liebig's Annalen*, Bd. lxi. (1866), S. 1.

† Dr. W. Allen Miller informs me that in 1845 he noticed a bright line in the spectrum of the diffused light of the oxyhydrogen jet reflected from a sheet of paper.

their being brighter relatively to the parts of the continuous spectrum where they occur, when the slit was directed from the side upon the gas immediately in front of the glowing part of the erbia.

The spectrum of bright lines obtained by means of the oxyhydrogen flame agreed more completely with the absorption spectrum represented by Bahr and Bunsen (No. 2 in their diagram) than the spectrum of bright lines figured by those observers (No. 3). The most important differences occurred in the band in the red, which showed two points of greatest brightness, thus forming a double line with a little outstanding light, and the line in the green at 65 of the scale, which was double, precisely as the corresponding absorption-line is represented in spectrum No. 2 of the diagram.

Lime.—The experiments were made with the cylinders of lime prepared for use with the oxyhydrogen blowpipe, and also with pieces of pure caustic lime; but there was no sensible difference presented in the spectroscope.

The bright lines consisted of a double line in the green, and several bands in the orange and red, which were found to form a spectrum identical with that which is produced when chloride of calcium is heated in the flame of a Bunsen's burner.

When the spectroscope was directed to a point in the flame a little above the incandescent portion of the lime, the lines appeared beyond the bright continuous spectrum, showing that they are not produced by the white-hot solid lime, but by the luminous vapour into which a portion of the lime has been converted by the heat of the flame.

Magnesia.—The commercial heavy oxide of magnesium was made into a paste with distilled water, and formed into a small pellet upon the end of a platinum wire. The pellet of magnesia was slowly dried, and then placed in the oxyhydrogen flame. I was surprised to see a spectrum of bright lines precisely similar to that which is produced by lime. Chloride of magnesium, when introduced into the Bunsen flame, gave a similar spectrum. I record these results as the oxide and chloride were those sold as pure. I found afterwards that a very small trace of lime may be detected in magnesia by means of the oxyhydrogen flame.

I then took metallic magnesium, which I had found by the spectroscope to be nearly pure, and formed from it magnesia and chloride of magnesium.

When this magnesia, formed into a small ball upon a wire, was subjected to the oxyhydrogen flame, two bright bands were seen in the green. One of these was found to be coincident with the triple line of Fraunhofer's *b*, which distinguishes magnesium, and the other with a group of bright lines which is seen between *b* and *F*, nearly in the position of the brightest double line of nitrogen, when metallic magnesium is burnt in air.

The chloride formed from magnesium, when introduced into the Bunsen

flame, gave the same bands, but the more refrangible band was exceedingly faint.

When an induction-spark was taken from a wire covered with cotton-wool soaked with a solution of the chloride, the lines at *b* and the more refrangible group were seen. If the heating-power of the spark be increased by the introduction of a Leyden jar, the band between *b* and F becomes scarcely distinguishable, while the lines peculiar to metallic magnesium are much more intense. When a spark is taken between electrodes of the same specimen of magnesium from which the chloride was formed, no trace of this band was detected.

Baryta.—When pure caustic baryta is subjected to the heat of the oxyhydrogen flame, a brilliant spectrum is seen identical with the well-known spectrum which presents itself when chloride of barium is heated in the Bunsen flame. Baryta furnishes a larger quantity of vapour than lime and magnesia, and therefore the lines could be traced to a greater distance from the solid baryta.

Strontia.—Pure strontia was fused into a large bead upon a platinum wire. When this bead was heated by the oxyhydrogen flame, the same spectrum of bright lines presented itself as is seen when chloride of strontium is placed in the flame of a Bunsen's burner.

Zirconia.—One of the small pellets of zirconia prepared in France for use with the oxyhydrogen blowpipe was found to give no trace of bright lines. This great fixity of zirconia as compared with lime is in agreement with the inalterability of the substance under the action of the oxyhydrogen flame.

Alumina.—Pure alumina treated in the same way as the magnesia gave a continuous spectrum only, without any trace of bright lines.

Glucina.—Glucina gave a bright line in the red, which I found to be due to potassium. Glucina, therefore, appears not to form vapour of any kind under the heat of the oxyhydrogen blowpipe.

Titanic acid gave a continuous spectrum without lines.

Oxide of uranium a continuous spectrum without lines.

Tungstic acid a continuous spectrum without bright lines.

Molybdic acid a continuous spectrum without bright lines.

Silica (precipitated) a continuous spectrum without bright lines.

Oxide of cerium a continuous spectrum without bright lines.

The question presents itself as to the nature of the vapour to which the bright lines are due in the case of the earths, lime, magnesia, strontia, and baryta. Is it the oxide volatilised? or is it the vapour of the metal reduced by the heat in the presence of the hydrogen of the flame? The experiments show that the luminous vapour is the same as that produced by the exposure of the chlorides of the metals to the heat of the Bunsen gas-flame. The character common to these spectra of bands of some width, in most cases gradually shading

off at the sides, is different from that which distinguishes the spectra of these metals when used as electrodes in the metallic state.*

Roscoe and Clifton have investigated the different spectra presented by calcium, strontium, and barium, and they "suggest that at the lower temperature of the flame or weak spark, the spectrum observed is produced by the glowing vapour of some compound, probably the oxide, of the difficultly reducible metal; whereas at the enormously high temperature of the intense electric spark these compounds are split up, and thus the true spectrum of the metal is obtained. In none of the spectra of the more reducible alkaline metals (potassium, sodium, lithium) can any deviation or disappearance of the maxima of light be noticed on change of temperature."†

As the experiments recorded in this paper show that the same spectra are produced by the exposure of the oxides to the oxyhydrogen flame, Roscoe and Clifton's suggestion that these spectra are due to the volatilisation of the compound of the metal with oxygen is doubtless correct.

The similar character of the spectrum of the bright lines seen when erbia is rendered incandescent would seem to suggest whether this earth may not be volatile in a small degree, as is the case with lime, magnesia, and some other earths. The peculiarity, however, of the bright lines of erbia, observed by Bahr and Bunsen, that they could not be seen in the flame beyond the limits of the solid erbia, deserves attention. My own experiments to detect the lines in the Bunsen gas-flame, even when a very thin wire was used, so as to allow the erbia to attain nearly the heat of the flame, were unsuccessful. The bright line in the green appears, indeed, to rise to a very small extent beyond the continuous spectrum, but I was unable to assure myself whether this appearance might not be an effect of irradiation.

It is perhaps worthy of remark that the chlorides of sodium, potassium, lithium, caesium, and rubidium give spectra of defined lines which are not altered in character by the introduction of a Leyden jar, and which, in the case of sodium, potassium, and lithium, we know to resemble the spectra obtained when electrodes of the metals are used. Now all these metals belong to the monad group; it appeared, therefore, interesting to observe the behaviour of the other metal belonging to this group.

Chloride of silver when introduced into the Bunsen flame gave no lines. The chloride was then mixed with alumina, which had been found to give a continuous spectrum only, and exposed to the oxyhydrogen flame, but no lines

* For the spectra of metallic strontium, barium, and calcium, see *Phil. Trans.*, 1864, p. 148 (pp. 408, 409), and Plates I. and II. Both forms of the spectra of these substances are represented by Thalén in his "Spektralanalyse."

† Roscoe's "Spectrum Analysis," p. 175, and *Proc. Lit. and Phil. Soc., Manchester*, April 1, 1862. See also A. Mitscherlich, "Ueber die Spectren der Verbindungen," S. 10.

were visible. When, however, the moistened chloride was placed on cotton and subjected to the induction-spark without a jar, the true metallic spectrum was seen, as when silver electrodes are used.

The behaviour of silver, therefore, is similar to that of the other metals of the monad group. Now the difference in basic relations which is known to exist between the oxides of the monatomic and polyatomic metals would be in accordance with the distinction which the spectroscope shows to exist in the behaviour of the chlorides; the chlorides of the polyatomic metals would be more likely to split up in the presence of water into oxides and hydrochloric acid.

In the case of some of the oxides and chlorides, one or more of the lines appeared to agree with corresponding lines in the metallic spectra; it may be, therefore, that under some circumstances, as in the case of magnesium burning in air, the metallic vapour and the volatilised oxide may be simultaneously present.

DR. REYNOLDS'S EXPERIMENTS

"After you observed the occurrence of two bright lines in the spectrum of the light emitted by incandescent lime, you recollect we identified these as belonging to calcium. At the time we supposed that these lines were produced by the ignition of the vapour of some volatile calcium compound probably present as an impurity in the sample of limes used in the experiments. If this explanation was found to be true of lime, the bright lines seen in the spectrum of erbia might possibly be accounted for in a similar manner. In order to examine the matter fully, I arranged the experiments described below.

"I selected two oxides for comparison with erbia—viz. lime and magnesia. As it seemed desirable to prepare these oxides in precisely the same manner as the erbia, some calcium and magnesium nitrates were made chemically pure to ordinary tests, and then used in the preparation of the respective oxides.

"The oxyhydrogen flame was employed as the chief source of heat. The hydrogen was made from zinc and sulphuric acid in the usual way, and the oxygen from potassium chlorate. As both gases are certain to be contaminated with traces of acids, I took the precaution of passing each gas through a long tube filled with fragments of solid potassium hydrate. If this plan were not adopted, the traces of acid which would find their way into the hydrogen or oxyhydrogen flame might produce volatile compounds with the earths, and so lead to mistakes.

"*1. Experiments with Magnesia.*—A loop of stout platinum wire was moistened with syrupy phosphoric acid, and some magnesium nitrate made to

adhere. The nitrate was then heated in the hydrogen flame, and a residue of magnesia obtained. No lines were observed in the spectrum of the light emitted by the incandescent earth, and when the latter was intensely heated in the oxyhydrogen jet only a continuous spectrum was seen.*

"2. *Experiments with Lime.*—A platinum wire of the same thickness as the last was moistened with phosphoric acid, some calcium nitrate was then taken up in the loop, and heated in the hydrogen flame until a residue of lime was obtained. At the outset the calcium-spectrum was observed, but the light speedily gave only a continuous spectrum. The lime and loop of wire were kept well enveloped in the hydrogen flame for nearly half an hour in order to ensure the complete decomposition of the nitrate. During this time no lines could be detected on the background of the continuous spectrum, or in the spectrum of the flame surrounding the lime. More hydrogen was now turned on and oxygen slowly admitted, the light being examined with the spectroscope during the time. When the proportion of oxygen had reached a certain point, faint traces of the two brightest Ca lines appeared on the bright background, and the intensity of these lines increased with the amount of oxygen admitted up to a definite extent. When a certain proportion of oxygen was exceeded, the lines became less distinct. The best results were obtained when the hydrogen was decidedly in excess of the oxygen in the flame, that is to say, more than in the proportion of 2 : 1.

"When the slit of the spectroscope was pointed in such a way that only the light from the flame surrounding the incandescent lime entered the instrument, all the Ca lines and bands were observed with great ease without a continuous spectrum. On looking at the mantle of flame with the naked eye it was easy to perceive a reddish tinge. I next maintained the small fragment of lime at the highest temperature its supporting wire was capable of resisting for *three hours*; at the end of this time the Ca lines were as strongly marked as before, and the lime on the wire had very appreciably diminished in amount. The same results were obtained when no phosphoric acid was employed to attach the calcium nitrate to the wire in the first instance.

"Again, a piece of well-burned quicklime, of very small size, was heated alone on a platinum wire for more than an hour, and the bright Ca lines were seen during the whole time.

"From the results of these experiments, we must draw the conclusions—(1) that when lime is sufficiently heated the light which it emits is derived in part from the incandescent solid, and partly from ignited vapour; (2) that lime is either volatile *as such*, or that in the first instance it suffers reduction

* "Since writing the above, I have succeeded in observing the bright lines described by Mr. Huggins as occurring in the spectrum of the flame surrounding the incandescent magnesia. In the earlier experiments I probably admitted too much oxygen to the mixed gas-flame in the first instance."

by the excess of hydrogen in the flame, the luminous vapour of calcium then giving its own peculiar spectrum.

" 3. *Experiments with Erbia.*—The specimen of erbium nitrate which you kindly gave me was attached to a platinum loop with syrupy phosphoric acid as usual, and decomposition of the salt effected in the plain hydrogen flame. After heating for a short time in this way, the chief green line of erbia became visible, but seen upon the continuous spectrum. Oxygen was now turned slowly into the flame. As the temperature rose, two of the other bright lines of the earth were seen. The best observations were made when the oxyhydrogen flame had hydrogen in excess, and the erbia was kept in such a position that it was very strongly ignited. The erbia lines were most distinctly seen when the slit of the spectroscope took in the light from the extreme edge of the incandescent solid. When the bright lines were best observed, the continuous spectrum was relatively faint. Again, when the slit was made to cut the edge of the ignited bead of the earth, the strong green line of erbia was seen to extend to a very small but appreciable distance above or below (as the case might be) the continuous spectrum. I could only observe this for the strong line. I failed to get any trace of lines in the spectrum of the flame beyond the incandescent erbia.

" The erbia was next heated in the oxyhydrogen flame to the maximum temperature that the wire would bear for *three and a half hours*, but the green line was seen to be just as strongly marked at the end as at the beginning of the experiment. The bulk of the erbia was so much reduced by this treatment that I have now scarcely a trace left.

" From the results of these experiments I think we must conclude—(1) that the light emitted by incandescent erbia is derived chiefly from the ignited solid, but that the bright lines observed in its spectrum have as their source a luminous vapour of extremely low tension at even the highest temperature of the oxyhydrogen flame; (2) that this interrupted spectrum belongs either to erbium or to its oxide.

" If these conclusions are true, it follows that erbia is not an exception to the ordinary law.

" It would appear that in these experiments three substances have been employed, varying in their degree of volatility. At the temperature of the oxyhydrogen flame magnesia appears to be less volatile than lime; but I am in doubt what relative volatility to assign to erbia, since its spectrum of bright lines can be seen when the earth is heated in the plain hydrogen flame, and yet at the much higher temperature of the oxyhydrogen jet the volume of luminous vapour does not appear to materially increase.

" Finally, we have yet to learn whether or not in all these cases reduction of the oxide precedes volatilisation; if reduction takes place, the luminous vapour

must be that of the metal. The settlement of this question would no doubt be very difficult. But I rather incline to the view that the vapour whose spectrum is obtained on igniting these earths is that of the metal; for I find that the bright lines are most easily observed when hydrogen is present in excess in the oxyhydrogen flame. Moreover, the actual amount of matter volatilised on very prolonged heating is really very small, and this circumstance appears to favour the view that a slow surface-reduction is in progress."

ON THE SPECTRUM OF THE FLAME OF HYDROGEN

(From *Proc. Roy. Soc.*, vol. xxx., p. 576, 1880)

MESSRS. LIVEING AND DEWAR state, in a paper read before the Royal Society on June 10 (*ante*, p. 494), that they have obtained a photograph of the ultra-violet part of the spectrum of coal gas burning in oxygen; and in a note dated June 8 they add that they have reason to believe that this remarkable spectrum is not due to any carbon compound, but to water.

Under these circumstances I think that it is desirable that I should give an account of some experiments which I made on this subject some months since without waiting until the investigation is more complete.

On December 27, 1879, I took a photograph of the flame of hydrogen burning in air. As is well known, the flame of hydrogen possesses but little luminosity, and shows no lines or bands in the visible part of the spectrum, except that due to sodium as an impurity.

Professor Stokes, in his paper "On the Change of Refrangibility of Light,"* had stated that "the flame of hydrogen produces a very strong effect. The invisible rays in which it so much abounds, taken as a whole, appear to be even more refrangible than those which come from the flame of a spirit lamp." I was not, however, prepared for the strong group of lines in the ultra-violet which, after an exposure of one minute and a half, came out upon the plate.

Two or three weeks later, about the middle of January 1880, I showed this spectrum to Professor Stokes, and we considered it probable that this remarkable group was the spectrum of water. Professor Stokes permits me to mention that, in a letter addressed to me on January 30, he speaks of "this novel and interesting result," and makes some suggestions as to the disputed question of the carbon spectrum.

I have since that date taken a large number of photographs of the spectra of different flames, in the hope of being able to present the results to the Royal Society when the research was more complete. I think now that it is desirable that I should describe the spectrum of the flame of hydrogen, but

* *Phil. Trans.*, 1852, p. 539.

I shall reserve for the present the experiments which relate to the presence of carbon and its compounds.

The spectrum of the flame of hydrogen burning in air is represented in the diagram, spectrum No. 1. It consists of a group of lines which terminates at the more refrangible limit in a pair of strong lines, $\lambda 3062$ and $\lambda 3068$. At a short distance, in the less refrangible direction, what may perhaps be regarded as the group proper, commences with a strong line, $\lambda 3090$. Between the strong line $\lambda 3068$ and the line $\lambda 3090$ there is a line less bright, $\lambda 3080$. Less refrangible than the line $\lambda 3090$ are finer lines at about equal distances. The lines are then fine and near each other, and appear to be arranged in very close pairs. There is a pair of fine, but very distinct lines, $\lambda 3171$ and $\lambda 3167$. In this photograph the group can be traced to about $\lambda 3290$. This group constitutes the whole spectrum, which is due probably to the vapour of water.

I then introduced oxygen into the flame, leaving a small excess of hydrogen. A spectrum in all respects similar came out upon the plate. I repeated the experiment, taking both spectra on the same plate. Through one half of the slit the spectrum of the oxyhydrogen flame was taken.

This flame was about 7 inches long, and the spectrum taken of a part of the flame 2 inches from the jet. The oxygen was then turned off, and the quantity of hydrogen allowed to remain unaltered. A second spectrum with an exposure of the same duration was then taken through the second half of the slit. On the plate the two spectra are in every respect similar, and have so exactly the same intensity that they appear as one broad spectrum.

In all these experiments a platinum jet which had been carefully cleaned was used.

In these experiments the two gases met within the blowpipe and issued in a mixed state.

The jet was removed, and a flame of hydrogen was surrounded with oxygen. The spectrum, No. 2 in the diagram, shows some additional lines. In this case the jet was brass, and in this or some

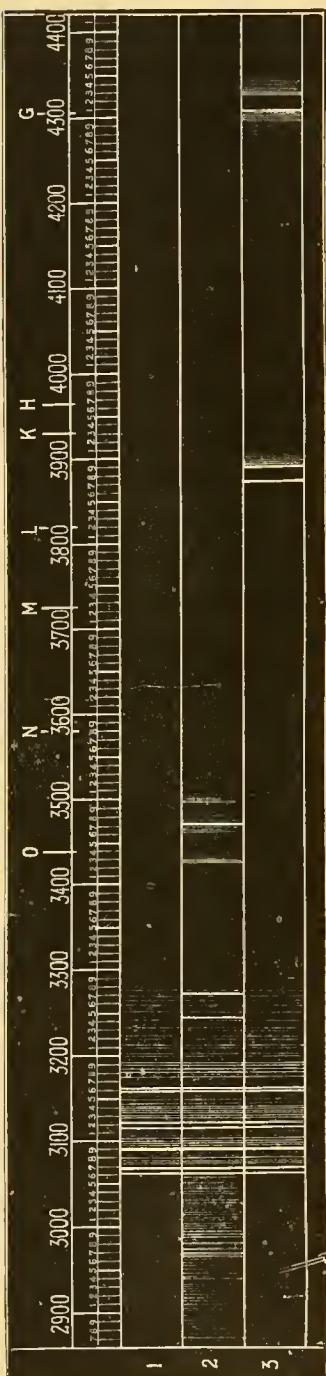


Fig. 49.

other way impurities may have been introduced; and I should, at present, incline to the view that the additional lines about λ 3429 and λ 3473, and the groups more refrangible than λ 3062, do not belong to the water spectrum, but to impurities.

Coal-gas was substituted for hydrogen in the oxyhydrogen blowpipe, and oxygen admitted in as large a proportion as possible. The inner blue flame rising about 2 inches above the jet showed in the visible part of the spectrum the usual "five-fingered spectrum." The light from this part of the flame was projected upon the slit. The spectrum, No. 3 in the diagram, contains the water group already described, and in addition a very strong line close to G, and two lines, λ 3872 and λ 3890; this latter line is seen to be the more refrangible limit of a group of fine lines shading off towards K.

The ultra-violet group, when carefully compared with the group in the spectrum of pure hydrogen, shows several small differences. I am inclined to believe that there is the superposition of a second fainter group. There is strong evidence of this in some spectra of hydrogen, taken under other conditions. There is also a broad band less refrangible than the strong line at G, and the light extends from this line on its more refrangible side.

A double Bunsen burner (Fletcher's form) with a strong blast of air was then fitted up. The spectrum was taken of the intense blue flame. It resembles the one last described. All the distinctive features are intensified, and a continuous spectrum and groupings of very fine lines fill up all the intervals between the groups already described, so that there is an unbroken strong spectrum throughout the whole region which falls upon the plate.

A spirit lamp was arranged before the slit. The spectrum is essentially the same as No. 3, but as it is less intense only the strongest lines are seen. The water group, the strong line at G, and the pair of lines rather more refrangible than K, are seen. Probably with a longer exposure the finer lines would also show themselves.

The distinctive features of spectrum No. 3 appear to be connected with the presence of carbon.

TABLE OF WAVE-LENGTHS OF THE PRINCIPAL LINES OF THE SPECTRUM OF WATER. NO. 1

3062	3095	3135	3171	3217·5
3068	3099	3139	3175	3223
3073	3102	3142·5	3180	3228
3074	3105	3145	3184	3232
3077·5	3111	3149·5	3189	3242·5
3080	3117	3152·5	3192·5	3252·5
3082	3122·5	3156	3198	3256
3085	3127	3159·5	3201	3262
3090	3130	3163	3207·5	3266
3094	3133	3167	3211	3276

WAVE-LENGTHS OF OTHER LINES IN SPECTRUM. NO. 2

2869·5	2910	2947	2991	3031
2872·5	2913	2951	2994	3039
2876	2917·5	2955	2999	3042
2880	2922·5	2959	3002	3046
2883	2925·5	2966	3005	3051
2887·5	2929	2967·5	3010	3057·5
2892	2932·5	2970·5	3013	3246
2895	2935·5	2975·5	3017	3271
2897	2940	2981	3019·5	3429·5
2904	2943	2989	3029	3473
2907·5				

WAVE-LENGTHS OF OTHER LINES IN SPECTRUM. NO. 3

3872	3890	4310
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NOTE ON THE PRECEDING PAPER

(Letter of Professor Stokes, from *The Pall Mall Gazette*, July 9, 1880)

SIR,—

In your impression of the 6th instant, in an article headed "Who speaks first?" occurs an illustration which I am sure the writer would not have used if he had been fully acquainted with the circumstances of the case.

In January last Mr. Huggins mentioned to me that he had found the flame of burning hydrogen on being photographed gave a whole series of lines in the ultra-violet region of the spectrum, and a few days later he showed me one of the photographs. We had some conversation on the subject, and it was suggested that the spectrum was really that of incandescent water. I rather think, but my recollection is not certain about this, that he expressed some doubts whether he had best publish the result he had obtained at once, or wait till he should have examined other flames. Be this as it may, he adopted the latter course.

A few months later Professor Liveing mentioned to me in conversation that Professor Dewar and he had observed a set of lines in the ultra-violet part of the spectrum which were referable to water, or appeared to be so. I, of course, said nothing about Mr. Huggins's discovery, which had been communicated to me in confidence; and having been thus made the confidant of both parties, I carefully abstained from saying anything to either which might have the effect of either accelerating or retarding the publication of their results.

Those who examine the *Proceedings* of the Royal Society will know that Professors Liveing and Dewar have for a considerable time been engaged

together in a careful examination of the spectra of the chemical elements and of some combinations. The further examination of the spectrum of water with a view to eliminating possible impurities and mapping it in detail naturally fell in with their work. The subject was fully worked out in time to send a paper to the Royal Society, which was read at the last meeting in June. It is true that in a paper read very shortly before, Professors Liveing and Dewar mentioned that they had been working at the spectrum of water, and promised shortly to send a paper on that subject; and it was doubtless this mention that induced Mr. Huggins to communicate a paper on his own work on the same subject, without waiting till the materials for a longer paper on the spectra of different flames were ready for publication. Mr. Huggins's paper on the spectrum of water was read at the same meeting as that of Professors Liveing and Dewar. We have therefore here another example, of which the history of science affords so many, of the same discovery being made perfectly independently and nearly simultaneously by independent workers following independent lines of research.

I will only add that in making the above communication I am acting in accordance with the wishes of both parties.

I am, Sir, your obedient servant,
G. G. STOKES.

ON THE RELATIVE BEHAVIOUR OF THE H AND K LINES OF THE SPECTRUM OF CALCIUM

(From *Proc. Roy. Soc.*, vol. lxi., p. 433, 1897)

THE remarkable relative behaviour of the lines in the spectra of certain substances as they appear at and near the sun's limb, and in the atmospheres of stars of different classes, has long been before our minds as a problem of great interest, which there is reason to believe is capable of solution by the methods of the laboratory, and on which we have worked from time to time for many years. Without waiting for the results of other researches which are in progress, we think that it is desirable to put on record some definite results on the behaviour of the lines of calcium, which appear to us to be conclusive, and of great importance in forming a correct interpretation of many solar and stellar phenomena.

As early as 1872, Professor Young, from a few weeks' work at Sherman on the spectra of the chromosphere and of the prominences, was able to point out that "the selection of lines seems most capricious; one is taken and another is left, though belonging to the same element, of equal intensity, and close beside the first." Especially he noticed that while the H and K lines

of calcium are almost always observable, the strong blue line as well as the other lines of this metal are very seldom seen. In his table of the chromospheric lines Professor Young gives for the frequency of this strong blue line the small number 3; while for the frequency of H and K he gives respectively the high numbers 75 and 50.

From 1863, when I mapped the spectrum of calcium with a strong spark from metallic calcium,* I have constantly used the lines of calcium as a comparison spectrum in stellar work. The experience was familiar to me that, as the quantity of calcium salt on the electrodes became very small, H and K continued strong even when the other calcium lines had almost disappeared. The suggestion then occurred to me, that this behaviour of the lines might furnish a clue to the phenomena which take place near the sun's limb.

We were encouraged to use this experience as a guiding thought in the experiments about to be described, by the consideration that in the higher solar regions, where H and K appeared alone of the calcium lines, the density must be much less than at the lower level of the reversing layer. It seemed very probable that in the simple fact of difference of density lay the true explanation of the modifications of the calcium spectrum as they are presented to us in solar and stellar phenomena.

The problem before us was, therefore, to find out, by experiments in the laboratory, under what conditions the lines of calcium other than the lines H and K, and in particular the strong blue line at 4226·9, were so greatly enfeebled relatively to H and K that they became quite insignificant, or even disappeared altogether from the spectrum, leaving the very simple spectrum of the two lines H and K, or nearly so.

Professor Lockyer states that "Some of the substances which have been investigated, including iron, calcium, and magnesium, have probably a definite spectrum, consisting of a few lines, which can only be completely produced at a temperature higher than any which is at present available in laboratory experiments." †

In the case of calcium :

"(4) A spectrum consisting of the two lines at 3706·18 and 3737·08 and the H and K lines, corresponding to a temperature higher than the average temperature of the spark, as before explained." ‡

Such a spectrum was not actually obtained, but experiments with a large intensity coil suggested that by a still greater increase of intensity of the spark such a simple spectrum might appear. The intensity of the strong blue line was reduced to one half of H and K. §

Kayser and Runge found 106 lines of the calcium spectrum to belong to

* *Phil. Trans.*, 1864, p. 139.

‡ *Proc. Roy. Soc.*, vol. lxi., p. 161.

† *Proc. Roy. Soc.*, vol. lxi., p. 205.

§ *Ibid.*, Table, p. 162.

the series of triplets ; among the remaining lines they pointed out pairs with constant differences of wave-frequencies : notably H and K, with a difference of wave-frequency of 222·9, and the more refrangible pair at 3737·08 and 3706·18, with a difference 223·1.

Messrs. Humphreys and Mohler in their experiments on the effect of pressure on the wave-lengths of metallic lines, found that in the case of calcium, the H and K lines were shifted only one-half as much as the blue line at 4226·9. We know far too little to justify us in forming any theoretical conclusions from this peculiarity of behaviour. Indeed there are no certain reasons why the lines of any substance should be equally shifted.

It is well known that calcium, in common with nearly all substances, gives a more complex spectrum under the conditions of the arc and spark than under those of a flame. Now in the Fraunhofer lines we have, as first shown by Kirchhoff and Bunsen, absorption spectra of the elements which correspond, speaking broadly, with those of the bright-lined spectra of the same substances as they are produced by the spark. In order, therefore, to study the modifications which the calcium undergoes in the higher regions of the chromosphere, in the prominences, and possibly in lower parts of the corona, as well as in the atmospheres of stars of different orders, it was clearly desirable that we should start with an ordinary spark spectrum. It was suggested to us strongly by the known rarer state of the gases in the regions above the photosphere, as well as by my long experience with the behaviour of calcium in comparison spectra, that the modifications of the calcium spectrum which we were seeking would be likely to show themselves under conditions of greatly reduced density of the calcium vapour.

EXPERIMENTS

For reasons which will be obvious later on, we elected to use throughout the experiments a spark of very small intensity.

1. The break of a 6-inch Apps coil was fixed at the position of smallest acting force of the spring. So much battery power only was employed as would be just sufficient to move the break. Under these conditions, when a jar was not in connection, the feeble spark would not pass when the distance between the points exceeded $1\frac{1}{4}$ inch.

2. In all the experiments a jar was intercalated.

3. The same length of exposure, a very short one of a second and a half, sufficient to bring out only the strongest lines of the spectrum, was used in each experiment.

4. Two sets of similar experiments were made ; in one case with electrodes of platinum, and in the other with electrodes of iron. In the latter case the chief lines of iron were present with those of calcium.

METHOD ADOPTED FOR REDUCING THE DENSITY OF THE CALCIUM VAPOUR

(a) The spark was taken between electrodes of metallic calcium. It was assumed, as was confirmed by the appearance of the spark, that with metallic calcium for electrodes, the largest amount of calcium vapour would be present.

(b) The tips of the electrodes, iron or platinum, were slightly moistened with a strong solution of calcic chloride.

(c) The tips were slightly washed with pure water.

(d) The tips were again washed with pure water.

(e) The tips were then slightly moistened with a very weak solution, made by adding a drop of the strong solution to 2 ounces of water.

Our expectations were completely confirmed. Under the conditions (a) of greatest density of the calcium vapour, when metallic calcium was employed, the blue line was as strong and possessed the same diffuse character as H and K.

As the density of calcium was reduced, the lines were not found to be equally enfeebled, but, on the contrary, the blue line and the greater number of the lines were increasingly reduced in intensity relatively to H and K, until at last, with the twice-washed electrodes (d) the spectrum was simplified to the condition usually existing in the prominences, in which H and K only are present.

We now proceed to a more precise statement of the changes of relative intensity as they are presented in the photographs which accompany this paper.

DESCRIPTION OF THE PHOTOGRAPHS ON THE DIAGRAM. (Fig. 50.)

A. Photograph of the spark when both electrodes consist of metallic calcium. Here we have present doubtless the largest amount and greatest density of calcium vapour. The winged character of H and K, of the blue line, and of the pair more refrangible than H and K, is well seen, showing that this appearance comes out when the gas is dense. If the greater extension of the wings of H is allowed for, and the line H carefully distinguished from the fine lines close to it, it will be seen to possess very nearly the same strength, both as regards width and length, as the blue line at 4226·9. The strength of this blue line under this condition of density is about the same as that of the line at 3737, and rather greater than the line beyond at 3706.

B. Spark taken with one electrode only of metallic calcium, the other electrode being of platinum. In this case the effect of a smaller density of the calcium vapour is clearly shown in the greatly reduced wingedness of the lines. It will be remarked that the diminished density has had the greatest influence on the pair at 3737 and 3706; these lines are now much less strong than the blue line, which still holds its own, and remains about as strong as

H and K. The lines of the more refrangible pair are no longer diffuse at the edges.

C. Spark taken between platinum electrodes moistened with a strong solution of calcium chloride. Here the effect of a smaller quantity of vapour begins to tell strongly upon the intensity of the blue line relatively to H and K. It may now be estimated at less than one-fourth of the intensity of H. At the same time, H and K have almost completely lost their diffuse character, and have become thinner and more defined.

D. The electrodes as left in the former experiment were slightly washed with pure water, leaving a trace only of calcium chloride. There is, as might be expected, an advance in the enfeeblement of the blue line and of the more refrangible pair, relatively to H and K.

E. The electrodes were again slightly washed with pure water, so that a

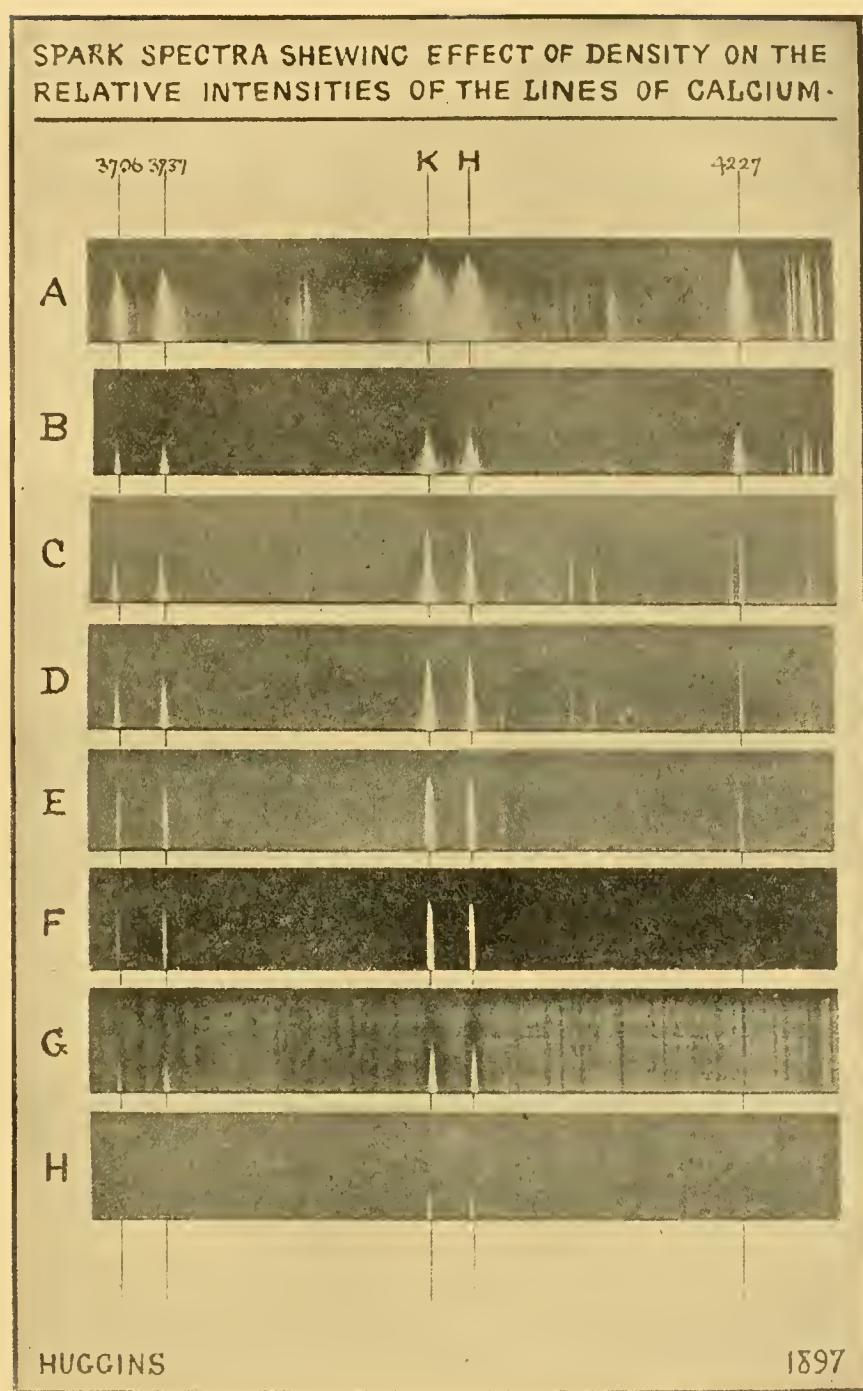


Fig. 50.

still smaller trace of calcium chloride must have remained upon them. The enfeeblement of the blue line and of the pair has now become very great, while H and K, though thinner, remain strong.

F. The electrodes were once more washed with pure water, reducing still further the trace of calcium chloride which remained upon the platinum wires. The blue line has now practically disappeared, and the refrangible pair become very thin. The H and K lines have become thin and defined, as they usually present themselves in the prominences.

G. The electrodes remaining as they were left after the last experiment (F), the spark was taken upon a background consisting of a faint solar spectrum. The blue line has now completely disappeared, leaving H and K strong.

H. Once more the electrodes were washed, with the expectation of having removed completely the last remaining trace of calcium. To our surprise, when the photograph was developed, the lines H and K came out alone. The more refrangible pair had now faded out as well as the blue line. H and K were now thin, and extended but a short distance in the spectrum.

It must be remembered that the only condition which was varied during this set of experiments was the amount or density of the calcium vapour. The changes of relative intensity, and the modifications of the calcium spectrum produced thereby as shown in the succession of photographs on the plate, correspond closely to the behaviour of calcium at different levels near the sun's limb, and in the atmospheres of stars of different orders. There can remain little doubt that the true interpretation of the changes in appearance of the calcium lines in the celestial bodies is to be found in the different states of density of the celestial gases from which the lines are emitted or by which they are absorbed.

A similar set of experiments was made with iron electrodes. Precisely similar results as to the relative enfeeblement of the lines, as with calcium chloride on platinum electrodes, were obtained. Of course the iron lines were also present. As might be anticipated, in consequence of the simultaneous presence of the iron vapour, the lines of calcium were thinner than when platinum was used.

Outside the range of wave-lengths which could be conveniently given on the plate, far on in the ultra-violet, there is a pair of strong lines which behaves very much as H and K. This pair remains visible in photograph H, when the pair at 3737 and 3706 has disappeared. The pair is situated at 3158·98 and 3179·45.

It is desirable to point out again that all the photographs on the plate and the far ultra-violet lines were obtained with a spark of quite unusually small intensity, which was purposely made as little hot as possible, in order to emphasize the important fact that the determining condition of the spectral changes under discussion is not one of increase of temperature.

In the modifications of the calcium spectrum arising from variations in the relative intensities of the lines which have been discussed in this paper, and which correspond to those observed in the celestial bodies, there does not appear to us any reason for assuming, much less any direct evidence in favour of, a true dissociation of calcium—that is, of its resolution into chemically different kinds of matter.

It would be remarkable if, by decomposition through increase of temperature, a large number of lines of a spectrum should become relatively enfeebled, and that as the result of decomposition a spectrum should become simpler, and not, as analogy would suggest, more complex.

It is of importance to keep in mind that the recent chemical use of the word *dissociation* is not equivalent to true decomposition, *i.e.* to a resolution of the original substance into two or more chemically different kinds of matter. It may, and does often, mean not more than a different arrangement of the parts of the molecule, while those parts are all chemically matter of the same kind as the original molecule—as in the case of the resolution of a compound molecule of peroxide of nitrogen into two identical half-molecules, or in the separation of a molecule of elementary iodine into two half-molecules or atoms of identical chemical characters. Such dissociations are well known, and are of not infrequent occurrence, and may, indeed, take place in connection with some of the spectral changes of a substance observed under different conditions. On the other hand, a true decomposition of a chemical element, that is, a breaking up of the molecule into simpler and quite other kinds of matter, though a notion familiar to chemists since Prout's time, and regarded as theoretically possible, is as yet unknown as a matter of fact.

CONCLUSIONS

These experiments seem to us to furnish an adequate and consistent explanation of the behaviour of the calcium lines at and near the sun's limb. Near the photosphere where the absorption mainly takes place, by which the dark lines of the solar spectrum are formed, there would be, we should expect, a much greater density of calcium vapour than at a higher level, and we find the Fraunhofer line at 4226·9 strong but much less broad than H and K. The recent photograph of the reversing layer shows that the broad shading of H and K is not produced there, but probably, as Professor Jewell concludes from his measures, lower down, where the gas is still denser, which is in agreement with photograph A on the plate.

Higher up in the chromosphere, in the prominences, and possibly in the lower coronal regions, the decrease of the density of the gases composing them must be rapid, and the temperature gradient as determined by expansion must be also rapid. We have clearly to do, in these regions, with calcium vapour in

a rarer state, and except so far as the molecules may have carried up within themselves to some extent the higher heat of a lower level, or through imperfect transparency, the gases may have received heat from the sun's radiation, it must be at a much lower temperature than near the photosphere. Now, the changes of the calcium spectrum which take place in these regions are those which correspond in our experiments to a very small amount of calcium vapour and a spark of small intensity.

On account of the violent commotion which must exist through the strong convection currents at the sun's limb, we should not be surprised to find some calcium vapour, notwithstanding its greater density, carried high up together with the lighter substances such as hydrogen and helium. Our experiments show how strongly the H and K lines may come out when a trace only of calcium vapour is present, and so, it seems to us, offer a possible explanation of the great height at which these lines may be sometimes recognised. At no very great distance from the surface of the sun the gases must become too tenuous to give a visible spectrum; but it may well be that the brilliant radiations of even very rare calcium gas at H and K may show in our instruments for some distance after the hydrogen and the other light matter associated with it have become too subtle to furnish a spectrum that we can detect.

The relative behaviour of the lines of the calcium spectrum as they present themselves in the different orders of stellar spectra when interpreted by the terrestrial experiments described in this paper, will throw much light on many of the important questions which are still pending in celestial physics. In forming conclusions as to the state of the stellar atmospheres from the different densities which may be indicated by the modifications of the calcium spectrum, it must be borne in mind that, as I have said elsewhere:

"The conditions of the radiating photosphere and those of the gases above it, on which the character of the spectrum of the star depends, will be determined not alone by temperature, but also by the force of gravity in these regions; this force will be fixed by the star's mass and its stage of condensation, and will become greater as the star continues to condense."*

It may be, though on this point we have as yet no sufficient data, that though the stars are built up of matter essentially similar to that of the sun, the proportion of the different elements is not the same in stars which have condensed in parts of the heavens widely distant from each other, or at epochs greatly separated in time.

It does not seem desirable to discuss any of these questions at the present time, as we hope before long to offer some explanation of the, to some extent analogous, relative behaviour of the lines of some other substances as observed in the sun and stars.

* Address, *Brit. Assoc. Report*, 1891, p. 15.

[The following letter from our friend Professor Liveing, which he has given us permission to publish, contains an account of early experiments on the spectrum of calcium which not only support, by a different method of working, the conclusions of our paper, but also seem to suggest the possible occurrence of the line H without the line K. In our experiments both lines were always present, the line K being longer and stronger than H—conditions of the calcium lines which are in agreement with the photographs of the prominences taken by Hale and by Deslandres.

"I have been looking up some observations of Dewar's and mine on the H and K lines of calcium made in 1879. We found that when we used, for the arc, carbon poles which had been heated for two days in chlorine to remove metals, the calcium lines were not at first visible in the arc, but after a time H was seen alone and not strong; after a further time, K was seen, and then other calcium lines came out. No doubt the calcium had been pretty well removed from the carbon rods to some depth, but not entirely from the interior, so that as the carbon burnt away in the arc the calcium in the interior became manifest.

"Again, we found that when we used a perforated pole and passed a stream of hydrogen into the arc through it, H and K could be both entirely obliterated; but by then reducing the current of gas they gradually reappeared, and H always came out first and afterwards K; and H remained stronger than K, until they had both resumed their ordinary appearance. This observation was repeated several times.

"Both sets of observations, those with the purified carbon poles and those with the perforated pole, seem to me to confirm your conclusions.

"In the case of those with the perforated pole, the stream of hydrogen diluted the calcium vapour, and the degree of dilution was controlled by the rate at which the gas was introduced. The mass of gas passing was too small to reduce the temperature by any considerable amount, or even, I should think, to any sensible amount.

"We found also that metallic lithium, introduced into the arc, produced effects similar to those produced by hydrogen, that is, that it reduced very much the strength of the H and K lines. If more than a very minute piece of lithium were introduced, the arc was invariably broken, so that we did not notice the complete obliteration of H and K with the lithium.

"The reduction of the strength of H and K, in this case, I attribute to the dilution of the calcium vapour by that of lithium."—June 25.]

PRELIMINARY NOTE ON SOME MODIFICATIONS OF THE MAGNESIUM
LINE AT $\lambda 4481$ UNDER DIFFERENT LABORATORY CONDITIONS OF
THE SPARK DISCHARGE

(From *Astrophys. Journ.*, vol. xvii., p. 145, 1903)

IN his "Note on the Wave-length of the Magnesium Line at $\lambda 4481$ "* Professor Crew points out that an interesting problem still remains—namely, to discover the laboratory conditions under which the line becomes sharp, as in some stellar spectra.

For some years, at intervals, experiments have been made here in the laboratory on the spectrum of magnesium, with the hope of throwing light on the physical conditions of the stellar atmospheres which we may assume to be indicated by the character of this line when present; a line which in the laboratory is subject to a very wide range of modifications, both of character and of intensity.

As it may be some time before these experiments are sufficiently complete for publication, it seems desirable to reproduce at once with this preliminary note, out of the very large number of spectra which have been taken, a few representing the most typical forms of the modifications of this line.

The teaching of these experiments suggests that the condition of the spark-discharge which is most potent in bringing about modifications of this line both in intensity and in character is the greater or less suddenness of the blow of the discharge. To a small extent only does the character of the line appear to be affected by the quantity and the electro-motive force of the electricity which is in action; indeed, such changes as may appear are probably brought about indirectly by the larger mass of material acted upon as the discharge is made more powerful.

The appearance of the line at $\lambda 4481$ in the spectrum at the top of the diagram may be taken as representing its normal condition with capacity in the secondary of the coil. When the jar is taken out of circuit, and the discharge of the secondary takes place directly between the magnesium electrodes, the line becomes thin, defined, and of small intensity, as in spectrum No. 2. In this case the electric blows are less sudden, through the incoming of the full self-induction of the coil itself.

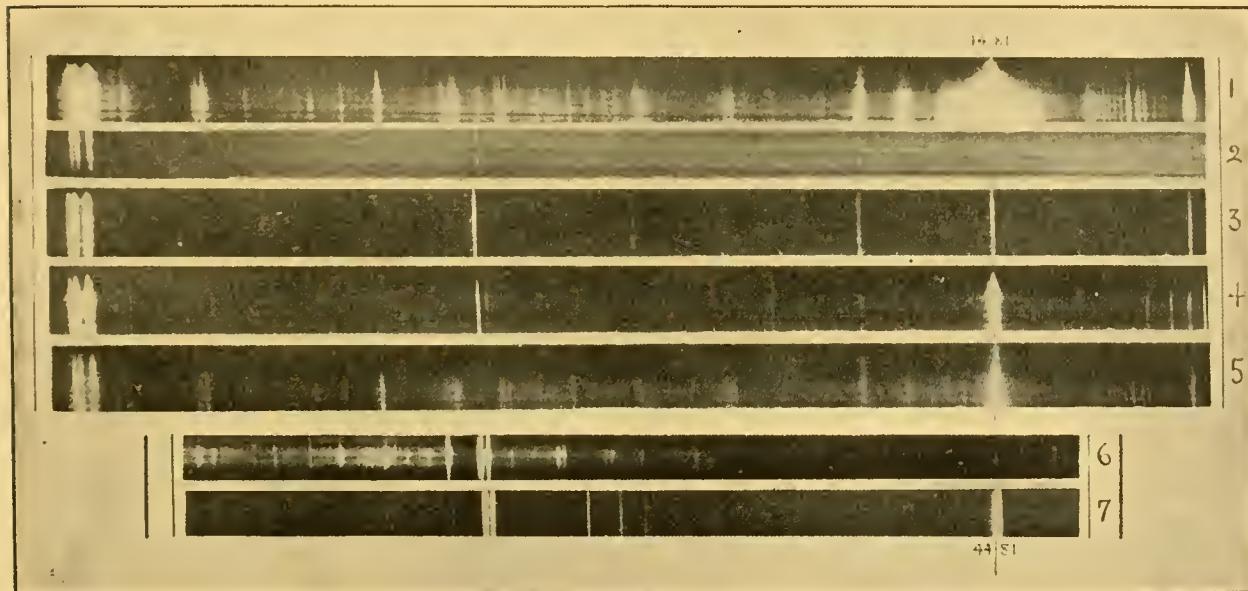
The researches of Schuster, Hemsalech, Schenck, Huff, and others have shown that a similar effect follows when the jar-discharge is slowed down by the introduction into the circuit of an independent self-induction. The condition of the line in spectrum No. 3 shows the effect of the introduction of a

* *Astrophys. Journ.*, vol. xvi., p. 246, 1902.

self-induction, the conditions of the discharge remaining otherwise the same as in photograph No. 1.

In spectrum No. 5 a stronger alternating current and a capacity four times as great as in No. 1 were employed; but the photograph is feeble from over-exposure. On the contrary, in No. 4 the coil was excited by a feeble continuous current, and the capacity in the circuit was reduced to a small jar.

The two spectra placed below were taken some years ago with another spectroscope. They are of interest in showing the great variation of intensity



SPARK SPECTRUM OF MAGNESIUM.

Fig. 51.

which the line at $\lambda 4481$ may undergo without assuming its normal diffused character, as in No. 1. The line in spectrum No. 4 appears to be intermediate in character between that of the line in No. 7 and that in No. 1.

We have still before us the task of the interpretation of the differences in the mode of production of the electric spark, especially as to greater or less suddenness, so as to enable us to connect them with definite conditions of temperature and density of those stellar atmospheres in which the magnesium present absorbs radiations similar in character to those photographed in the laboratory.

ON THE SPECTRUM OF THE SPONTANEOUS LUMINOUS RADIATION
OF RADIUM AT ORDINARY TEMPERATURES

(From *Proc. Roy. Soc.*, vol. lxxii., p. 196, 1903)

THE discovery of an element possessing such remarkable and novel properties as radium, which in its separate and distinct form as a new chemical element we owe to the researches of Professor and Mme. Curie, has already thrown many beams of suggestive light into the very obscure regions of the constitution of matter. In radium we have a body which appears to be spontaneously and without ceasing giving off energy in several forms. According to Professor Rutherford,* following upon the work of Becquerel, M. and Mme. Curie, and others, the emanations going off from radium are at least of three kinds. First, an emanation of heavy corpuscles, larger in mass than the hydrogen atom, moving with a high velocity, and carrying a positive charge; secondly, of negatively charged electrons which form a powerful and penetrating cathode emanation; † and further, of a radiation of a very penetrating character. In addition, M. and Mme. Curie have found that radium spontaneously maintains a temperature about $1^{\circ}50$ C. above the surrounding temperature, and therefore emits heat radiations of wave-lengths falling within the infra-red part of the spectrum.

Now, in addition to these forms of radiant energy, the glowing of radium in the dark shows that it emits a luminous radiation spontaneously at ordinary temperatures. It appeared to us probable that in this glow we had not to do with either phosphorescence or fluorescence as usually understood, but with an independent and continuous radiation set up by those more active molecules which are supposed, in consequence of a condition of internal instability, to be the source of all the phenomena of radio-activity, and which can scarcely fail themselves to be violently agitated, in connection with disruptive molecular changes—especially the flinging off of the heavy corpuscles—during which, part of the energy stored up within the molecule is liberated in the kinetic form.

Taking this view of the luminous radiations visible to the eye, it seemed highly probable that the molecular motions by which they were set up, whether we suppose all the radium molecules alike to be concerned, or those only which are in active change, would be so far analogous to the vibrations pro-

* *Phil. Mag.*, April and May.

† As an illustration of the penetrative power of the radio-active effects of pure radium bromide, the following experience may be recorded here. About 1 centigramme of radium bromide (Buchler & Co., Brunswick) had been placed in an upper drawer of my writing table, while in a lower cupboard of the same table was a store of photographic plates. After a week or two, all the plates, in boxes lying upon each other three or four deep, were found to be as completely fogged as if they had been exposed to light.

duced artificially, when radium vapour is rendered luminous in a flame, or by the blow of an electric discharge, as, in like manner, to set up radiations of certain definite wave-lengths or, in other words, to furnish a spectrum of bright lines.

A preliminary prismatic examination of the glow from pure radium bromide was attempted by eye. In consequence of the feebleness of the light under dispersion a slit spectroscope could not be used. A thin fragment of some length of radium was selected, which in the dark shone as a narrow line of light; when this was viewed through a direct-vision prism, it was seen to be dispersed into a spectrum which extended from the blue down to about D, where it became too faint to be traced farther in the direction of the red. Within this faint spectrum certain spots were distinctly brighter, due, in all probability, to the presence of bright lines at those positions in the spectrum.

The success of this preliminary observation encouraged us to hope that it might be possible, by availing ourselves of the accumulative power of continuous photographic exposure, to obtain a record of the blue, violet, and ultra-violet regions of the spectrum, if the glow radiations extended so far.

We made use of a small quartz spectroscope which had been constructed some years ago for very faint celestial objects. It consists of a compound quartz prism of 60° , consisting of two prisms of 30° of right-handed and left-handed quartz respectively. The quartz lenses are of short focus and of large angular aperture, being about $\frac{1}{3}$ f. The focal length of the lenses is $5\frac{3}{4}$ inches; they are plano-convex, the marginal parts of the convex surfaces being "figured" to diminish spherical aberration.

The solid radium bromide was placed at about a millimetre distance in front of the slit, which had to be wider than if a bright object were being photographed; the width was about $\frac{1}{450}$ th inch. In the case of the spark spectrum of radium and the comparison spectrum of nitrogen, a slit of less than half this width was used.

With an exposure of 24 hours, faint traces of two lines were seen on the plate. After several trials the negative reproduced on the accompanying plate was obtained with an exposure of 72 hours. The reproduction is enlarged two and a half times. The spectrum consists of eight bright lines, and at least eight faint lines, together with a faint trace of continuous spectrum in the blue region, which does not come out in the reproduction.

It was seen at once that the two very strong characteristic rays of the spark spectrum of radium, in this part of the spectrum—namely, 3814·5 and 3649·6*—were not present on the plate. It was clear that the spectrum was

* For spark spectrum of radium, see Demarçay, *Comptes rendus*, vol. cxxix., p. 786, and vol. cxxxii., p. 258; Exner and Haschek, *Wien. Akad. Sitzber.*, vol. cx., July 1901; Runge, *Astrophys. Journ.*, vol. xii., p. 1.

not that of the radium molecule when excited by the electric discharge. It was indeed not improbable that if the radiation came alone from the most active molecules, which were suffering loss by material emanations, then, if we may accept the analogy from sound, like a filed tuning-fork they would no longer give radiations of the same wave-lengths as before.

As soon as measures were taken of the lines it was found that several of them agreed in position within the uncertainty of the measures with lines in the spectrum of helium, but not with the most characteristic helium lines in this part of the spectrum. Now Rutherford and Soddy had pointed out * the almost invariable presence of helium in minerals containing uranium. It seemed, therefore, not impossible that we might have to do with helium contained within the radium bromide, and that this gas was being liberated in connection with the active molecules in a state of molecular vibration, analogous to that set up in gaseous helium by an electric discharge.

[Received August 5.—Further examination of the new spectrum, stimulated by the unsatisfactory fact that the strongest lines of helium were not represented in the spectrum from radium bromide, has shown, quite unexpectedly, that if the new spectrum were slightly shifted relatively to the scale, then the seven strongest lines would agree not only in position, but also in relative intensity and character, with bands of the spectrum of nitrogen.

Now, the wave-lengths of the new spectrum had been found from a fiducial comparison solar spectrum, taken on the same plate. The slit is furnished with three shutters, of which the middle one only was open during the long exposure to the radium bromide. When the exposure was over, the middle shutter was closed, and the two side shutters opened, while the spectroscope was directed for a fraction of a second to the sky. As in both cases the collimator lens was filled with light, it was concluded that the wave-lengths would be correct. It is true that the spectroscope had to be placed in a different position for exposure to the sky, but as the instrument is very short and strongly constructed, it was not considered possible that any shift from flexure could arise.

The agreement with the bands of nitrogen is so complete that, though we are unable to trace any cause of shift, we feel justified in shifting the new spectrum on the diagram so as to bring the lines into agreement with those of nitrogen. The amount of shift at the position of the strongest line is nine tenth-metres, which, on the photographic plate, corresponds to the space of $\frac{1}{150}$ th of an inch.

The positions of the three bands are, according to Ames, † 3576·85, 3371·2, and 3158·9.

* *Phil. Mag.*, 1902, p. 582, and 1903, pp. 453 and 579.

† *Ibid.*, vol. xxx., p. 57, 1890. See also Deslandres, *Comptes rendus*, vol. ci., p. 1256; and Percival Lewis, *Astrophys. Journ.*, vol. xii., p. 8.

Indications of other lines, besides those which can be seen in the reproduction, can be faintly glimpsed on the negative. There seems little doubt that with a longer photographic exposure a more complete spectrum will be obtained. We have now secured some radium bromide prepared by the Société Centrale de Produits Chimiques, and it is our intention to take photographs of this salt, as well as photographs of the German salt, with longer exposures. It may then be, that indications of helium, and possibly of radium itself, may be forthcoming.

Nearly the whole of the ultra-violet radiations appear to come from nitrogen,

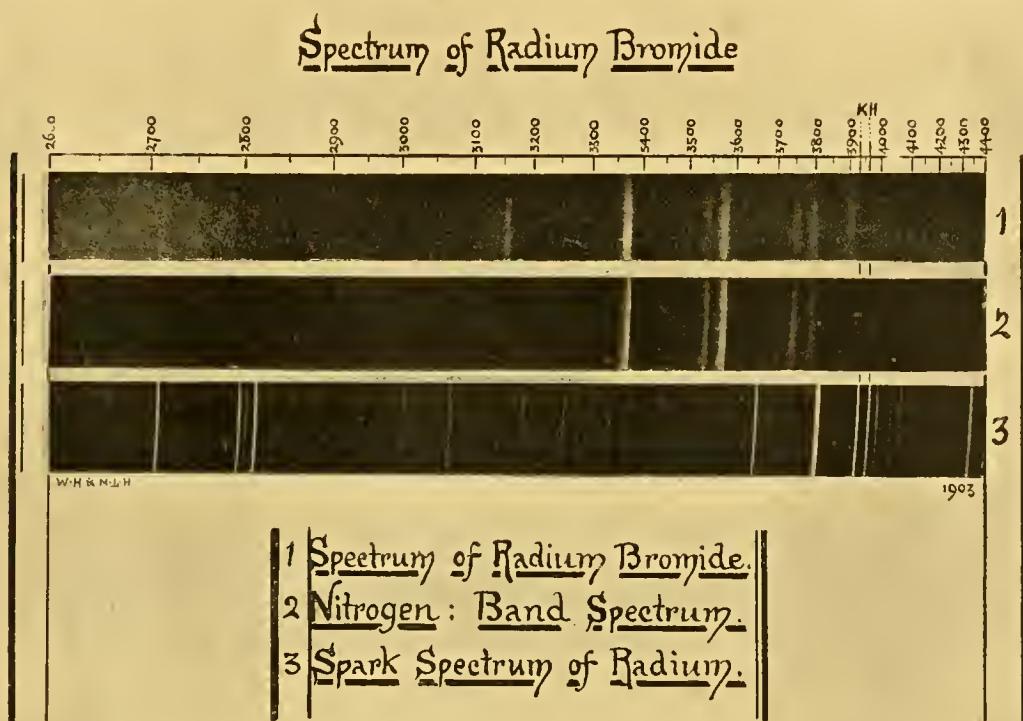


Fig. 52.

and we think it best to refrain from any discussion at this moment. Have we to do with occluded or with atmospheric nitrogen? The remarkable fact should be pointed out that in radium we have a body which, at the ordinary temperature, sets up radiations which are similar to those which have hitherto only been obtained in connection with the electric discharge.

Description of the Diagram.—At the top is placed a scale of approximate wave-lengths. Immediately below is a reproduction, enlarged two and a half times, of the spectrum obtained from the radium bromide with an exposure of 72 hours. As has been already explained, this has been shifted to bring the

lines into position with those of nitrogen photographed from a vacuum tube. The identity of the two spectra seems complete. The third band is faint in the nitrogen spectrum on account of the absorption of the glass of the tube.

Below, is a spark spectrum of radium bromide from the Société Centrale de Produits Chimiques. The H and K lines of calcium are present, as well as faintly some of the stronger lines of barium. The characteristic lines of radium at 3814·59 and 3649·7 come out strongly, as well as the strong line recorded by Demarçay at 4340·6. A strong line about 2710 was placed by Berndt* at 2708·6. The strong line a little beyond, about 2814, is due to radium. We do not recognise several lines recorded by Exner and Haschek † in this part of the spectrum.]

FURTHER OBSERVATIONS ON THE SPECTRUM OF THE SPONTANEOUS LUMINOUS RADIATION OF RADIUM AT ORDINARY TEMPERATURES

(From *Proc. Roy. Soc.*, vol. lxxii., p. 409, 1903)

In the diagram accompanying our paper on the spectrum of the glow of radium bromide,‡ at least seven lines are seen to agree, both in position and in intensity, with corresponding lines in the band spectrum of nitrogen. We called attention to other lines, of which some traces may be detected on the plate, and we suggested that with a longer exposure a more complete spectrum would be obtained. One strong line in the radium bromide glow spectrum, about 3914, has no similar line corresponding to it in the band spectrum of nitrogen as given on the plate.

We have since taken photographs, with longer exposures, of two specimens of radium bromide, one prepared by Buchler and Co. and the other received from the Société Centrale de Produits Chimiques. In these photographs, lines only faintly glimpsed in our earlier photographs can be seen distinctly. A photograph taken of the French radium bromide, with an exposure of 216 hours, is reproduced in fig. 53.

The coincidence of the spectrum with the band spectrum of nitrogen is shown to be even more complete by the presence of a faint trace of the next more refrangible band, beginning at 2976·7. In addition, some of the fainter single lines of the nitrogen spectrum now come out in the radium bromide spectrum.

At the same time that the coincidence down to minuter details with the nitrogen band spectrum is brought out, the strong outstanding line, about

* *Phys. Zeitschr.*, vol. ii., No. 12 (1900-1901).

† *Sitzb. Ak. Wiss. Wien*, vol. cx., July 4, 1901.

‡ *Proc. Roy. Soc.*, vol. lxxii., p. 196.

3914, is now seen to be accompanied by a second, but less intense, outstanding line at about 4280; neither of which is present in the ordinary band spectrum of nitrogen, which was the one reproduced on the plate of our first paper.

This nitrogen band spectrum is the one distinguished by Deslandres as that of the positive pole, but it appears at all parts of a vacuum tube, and is also produced when a suitable induction-coil discharge, without capacity, is taken across air at the ordinary density. The nitrogen spectrum that was measured by Ames was taken by using an end-on vacuum tube closed with a quartz plate; in his list no lines are given at the places of the two outstanding lines in the glow spectrum.

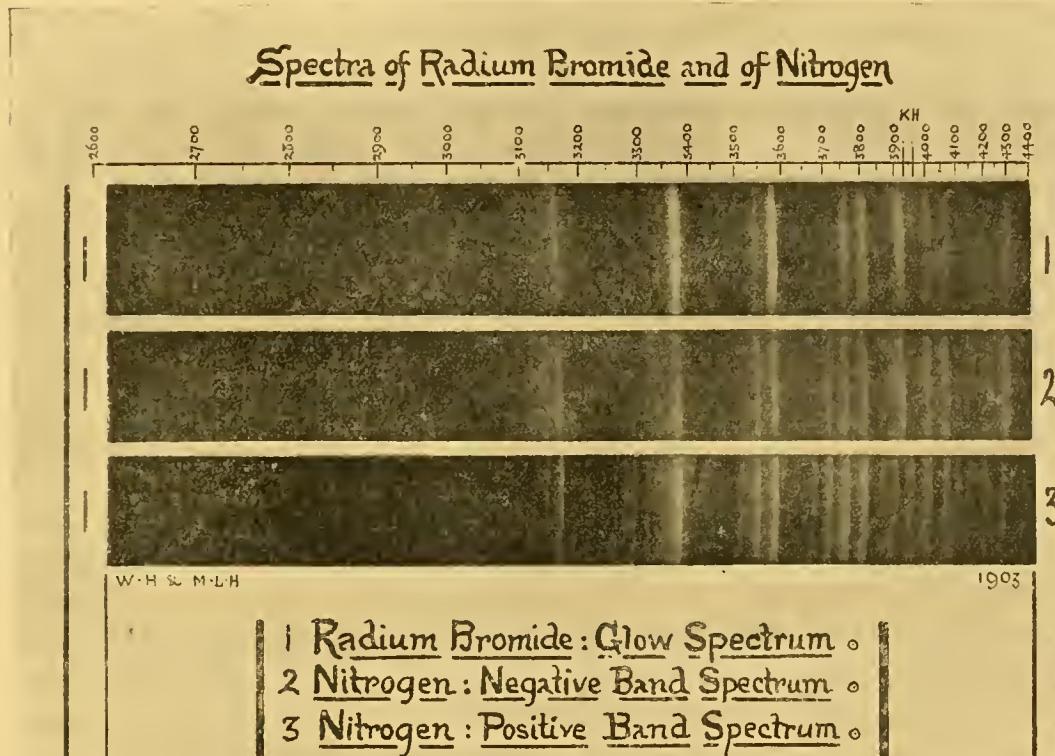


Fig. 53.

When, however, the spectrum is taken of the aureole about the negative pole of a vacuum tube containing a residuum of atmospheric air, the ordinary, or positive-pole spectrum becomes enriched by a new spectrum of bands; and in this additional spectrum the heads of the two strongest bands in the photographic region occur at the positions of the two outstanding lines of the

radium glow spectrum.* In the diagram are given, below the more complete radium spectrum now obtained, the ordinary band spectrum of nitrogen, and also the same spectrum enriched with the bands peculiar to the aureole of the negative pole. This latter spectrum corresponds to that of the radium glow. The peculiar conditions, whatever they may be, which determine the presence of these additional negative-pole bands must find their counterpart in the nitrogen molecules when under stimulation by the radium bromide. The additional bands which show themselves in the spectrum of nitrogen when taken from the glow at the negative pole of a vacuum tube are usually believed to be associated with the stimulation of the very rapidly moving corpuscles of the cathode stream. Accordingly, the presence of these negative-pole bands in the spectrum of nitrogen, when excited by radium, naturally suggests whether the β rays, which are analogous to the cathode corpuscles, may not be mainly operative in exciting the radium glow. On this surmise it would be reasonable to expect some little extension of the glow outside the radium itself. We are unable to detect (by eye) any halo of luminosity outside the limit of the solid radium bromide; the glow appears to end with sudden abruptness at the boundary surface of the radium.

It may be that it is only at molecular distances, and at the moment of their formation, that the rays can excite the nitrogen molecules.

As the glow spectrum is produced by the influence of the radium on nitrogen at the atmospheric pressure, it seemed to be of interest to find out whether the negative-pole spectrum could be obtained in air at the ordinary pressure. It has already been stated that when a suitable discharge of an induction coil, without capacity in the circuit, is taken between electrodes in air, the ordinary band spectrum of nitrogen appears. Separate photographs, therefore, were taken of the parts of the discharge in the close neighbourhood of the two electrodes, which were about three-eighths of an inch apart. The bands peculiar to the negative pole of a vacuum tube were found upon the plate taken of the negative electrode.

As the radium glow consists of light from nitrogen molecules stimulated into luminosity by the presence of the more active radium molecules, or of their radiations, it was reasonable to suppose that the bromine molecules, chemically associated with the latter, might also be sufficiently stimulated to

* Deslandres' measures, reduced to Rowland's scale, of the heads of these two bands are 3914·4 and 4279·6 (*Thèses*, 1888, Gauthier-Villars, and *Comptes rendus*, vol. ci., p. 1256). Ångström and Thalén give 4281·6 for the less refrangible band (*Nova Acta Upsal* (3), vol. ix., 1875). Hasselberg's measure for the head of the less refrangible band is 4378·6 (*Mém. de l'Acad. St. Petersb.*, vol. xxxii., No. 15). Percival Lewis on "Some New Fluorescence and Afterglow Phenomena in Vacuum Tubes containing Nitrogen" (*Astrophys. Journ.*, vol. xii., p. 8) found fluorescent nitrogen to give a band spectrum; and, in some conditions of the fluorescence, the most intense bands were those of wave-lengths 3576·9 and 3371·2.

reveal their presence by the lines in the spectrum peculiar to them. Photographs were accordingly taken of the poles of a vacuum tube containing traces of atmospheric air together with bromine vapour. The band spectrum of nitrogen appeared alone upon the plates when no capacity was introduced; but with the intercalation of a jar, the lines of bromine came out in the photographs, in addition to the lines of air. The experiment was then repeated at atmospheric pressure by enclosing platinum electrodes in a glass bulb communicating with the atmosphere by a narrow tube. Photographs of the coil discharge taken between them revealed the ordinary band spectrum of nitrogen. A few drops of bromine were then introduced into the bulb, filling it with bromine vapour. Photographs were again taken of the discharge in the air now heavily laden with bromine, but the spectrum remained precisely the same as before the bromine was introduced, namely, that of nitrogen only.

We may find in this experiment possibly a reason for the absence of any of the lines of bromine in the glow spectrum: it may be that stimulation from the active radium molecules affects preferentially the nitrogen molecule, so that this molecule can be shaken into luminosity by a stimulation which is insufficient to excite the bromine molecule to a comparable extent.

The experiment then suggested itself whether, under similar conditions of discharge, radium itself, when placed upon the electrodes, would be able to show its presence by its characteristic lines in the spectrum of the discharge taken between them. The result was negative, as in the case of bromine, no lines other than those of nitrogen appearing upon the plate. A small jar was then put into the circuit and another photograph taken, when the complete spectrum of radium came out strongly, but without the band spectrum of nitrogen.

If, as suggested by Rutherford, the α rays are connected with helium, the experiment seemed worth making of taking a photograph of the spectrum arising from their bombardment upon a zinc sulphide screen. It seemed possible, though not very probable, that the encounters of these bodies, at the enormous speed at which they travel, with the molecules of air, and their final collision with the screen, might on that hypothesis give rise to some of the radiations peculiar to helium, and so produce its spectrum on the plate. Fortunately the strong continuous spectrum due to the fluorescence of the screen ends abruptly in the violet a little before the place, at 3889, of the strongest line of helium in the photographic region, and so leaves the spectrum quite free for the detection of this line, even if it were only faintly present. The result of the experiment, so far as concerns helium, was negative; which must not of course be interpreted as excluding the presence of helium, but

only as showing that, if present, the conditions are not favourable to the appearance of its spectrum.*

On the first photograph that was taken, the two strongest lines of the nitrogen band spectrum were faintly seen, but a photograph with a new screen and a longer exposure showed no trace of the nitrogen bands. In the first case it might be, that some very minute particles of radium bromide had attached themselves to the screen, and by their independent glow had given rise to the lines of nitrogen which were on the photographic plate.

About 1 centigramme of French radium bromide, which was in the form of small particles, was put into a very small glass tube scarcely larger than was necessary to contain it. The tube was securely closed and left for two months. As the α rays, being unable to escape, would probably occupy the interstices between the radium bromide particles, it seemed desirable to examine whether as helium, or still in some precedent condition, they would show their presence in the glow spectrum. The tube was exposed, immediately in front of the slit, for 168 hours. The spectrum shows a strong continuous spectrum from the fluorescence of the glass, and faintly the bands of nitrogen, but no other lines with certainty. We intend to photograph again the spectrum of the glow from this tube, after a longer time has passed for an accumulation of the α rays and of the gas-like emanation.

When the radium bromide is covered with a plate of quartz, the continuous spectrum, due to the fluorescence of the quartz, is not only strong, but extends a long way into the ultra-violet. It can be traced on the photograph as far as 2500.

After a few hours the quartz darkens under the action of the radium bromide, the bluish-brown stain extending through the complete substance of a plate one-tenth of an inch in thickness. The stain is due probably to the reduction of silicon.

Experiments were made in the hope of throwing light upon the shift found in the photograph of the radium glow spectrum, reproduced on the plate of our first paper. As subsequent photographs of this spectrum were entirely free from any trace of shift, the shift found on the first plate must have been accidental. Repeated photographs, taken with the spectroscope in different positions, failed to show the smallest trace of shift from flexure. The only suggestion we can make in explanation is that the piece of solid radium bromide accidentally shifted in its cell, so as no longer to be directly under

* M. Henri Becquerel has quite recently investigated the scintillation observed on a phosphorescent screen when excited by radium. He comes to the conclusion: (1) "Ce sont les rayons α qui provoquent la phosphorescence scintillante"; (2) "Ces faits établissent sinon une démonstration, du moins une grande présomption en faveur de l'hypothèse qui attribuerait la scintillation à des clivages provoqués irrégulièrement sur l'écran cristallin par l'action continue plus ou moins prolongée des rayons α ." (*Comptes rendus*, vol. cxxxvii., pp. 633, 634, October 27, 1903.)

the slit, and in consequence the collimator lens was not wholly filled with light.

The results of the experiments described in this paper would appear to show generally, if analogy with electric stimulation may be assumed, that the radium stimulation, whether we take the operative cause to lie in the β rays, or in the encounters of nitrogen molecules with the active molecules of radium—by which, for the first time, a spectrum of bright bands in the ultra-violet region has been obtained at ordinary temperatures, and without the intervention of an electric discharge—from the very circumstance of its being of such a nature as to give rise to the band spectrum of nitrogen, is not of a kind which can elicit from either the molecules of bromine or of radium their characteristic line spectra.

The question suggests itself whether or not the same inability may hold in respect of the helium molecule, which is easily stimulated by an electric discharge; we have not as yet made experiments on this point.

ON THE SPECTRUM OF THE SPONTANEOUS LUMINOUS RADIATION OF RADIIUM. PART III.—RADIATION IN HYDROGEN

(From *Proc. Roy. Soc.*, vol. lxxvi., p. 488, 1905)

As soon as we found * that the glow of radium bromide consisted mainly of light from nitrogen stimulated into luminosity by the radium, and giving the negative pole spectrum, we formed the intention of photographing the spectrum of the glow when the radium bromide was placed in an atmosphere of hydrogen, primarily in the hope of finding an answer to the question raised in our first paper, "Have we to do with occluded or with atmospheric nitrogen?" †, and, in the second place, to determine whether the radium is able to render hydrogen luminous.

In these experiments some unexpected results came out, which made it desirable to repeat them many times. This circumstance, together with the long exposures necessary—from 10 to 14 days—and the slow changes which we found to take place in the radium when allowed to remain in the hydrogen for long periods, reckoned in months, have necessarily delayed the publication of this paper. The investigation is still in progress, but it seems desirable not to delay any longer the publication of the results which have been already obtained.

An account of each experiment would make the paper long and unnecessarily tedious. It will be sufficient to give the results of each group of experiments made under similar conditions. The same form of apparatus was

* *Proc. Roy. Soc.*, vol. lxxii., pp. 196 and 409.

† *Ibid.*, p. 199.

used for all the experiments. Small glass vessels were prepared, consisting of a round cell with flat base, to hold the radium, into which, on opposite sides, tubes of small bore were blown, the walls of the cell were ground flat on the top to receive a thin microscopic cover-glass, or a thin plate of quartz, which was cemented down after the radium salt had been placed on an ebonite support within the cell.

As the glow of radium takes place at atmospheric pressure, it was desirable that experiments with hydrogen should be made under like conditions. A current of hydrogen was allowed to flow through the glass vessel for some minutes until all traces of air must have been carried out; the two tubes were then sealed up, leaving the radium in hydrogen at atmospheric pressure.

Afterwards, a second series of experiments was made with hydrogen at reduced pressure. The glass vessel was connected with a vacuum pump and exhausted to below 1 mm. of mercury; hydrogen was then allowed to enter. The vessel was again exhausted and refilled with hydrogen several times, and was then sealed up with the contained hydrogen at the pressure of about 1 mm. of mercury.

Portions of the same two specimens of radium bromide which had been used in our former experiments were employed—namely, one from Buchler & Co., Brunswick, and the other from the Société Centrale de Produits Chimiques, Paris.

The results of repeated experiments made in hydrogen at atmospheric, and also at reduced, pressure, and with both samples of radium bromide, were uniformly similar. The glow became sensibly fainter to the eye when the radium had remained for a few days in hydrogen; perhaps the diminution of the brightness took place sooner in hydrogen at reduced pressure. Photographic plates, exposed in the spectroscope to radium in hydrogen for the same time as to the same radium in air, showed a feebler spectrum, which was that of nitrogen without any traces of the lines of hydrogen.

From these experiments we may assume either the existence of occluded or combined nitrogen, or that the spectrum was due to minute traces of air which had remained within the vessel. If, however, the increasing feebleness of the glow was due to the latter cause, we should expect that on unsealing the tubes and admitting air, the glow would at once recover its original brightness. On April 15, 1904, when the radium had remained 26 days immersed in hydrogen, the tubes were opened and air blown through, but no recovery of brightness as estimated by the eye took place at the time. Then a photographic plate was exposed in the spectroscope for seven days, on which, when developed, the nitrogen spectrum was even feebler than on a similar plate which had been exposed for the same time before the air was admitted. A few days later, however, a small increase of brightness was

detected by the eye, which continued until the radium slowly recovered its original brightness.

When radium was allowed to remain for months in an atmosphere of hydrogen some unlooked-for results were observed.

Experiment 1.—A portion of the Brunswick radium bromide was sealed up in hydrogen at reduced pressure on June 24, 1904.

(a) As in former experiments, the brightness of the radium bromide, as estimated by eye, gradually diminished.

(b) Photographs taken with the spectroscope showed the nitrogen spectrum only, and with increasing feebleness as time went on, until the strongest of the nitrogen bands only were just suspected upon the plate.

(c) Some days after sealing up in hydrogen, the radium bromide, which was originally of a yellowish cream-colour, began slowly to become darker, until by August 9, 1904, it had reached a dark russet brown.

(d) On March 17, 1905, the radium, which had now been sealed up for nearly eight months, was observed by eye to have become much brighter, indeed nearly as bright as the French radium which had remained in air. Unfortunately the radium in the hydrogen had slipped out of the ebonite support to the bottom of the cell, and therefore could not be brought before the slit of the spectroscope. It was then decided to open the vessel and remove the radium in order to photograph its spectrum while in this brighter condition. Before placing it in the spectroscope it was thought desirable to compare it again at night, about eight hours after it was taken out of hydrogen, with radium which had remained in air. To our great surprise the radium removed from the hydrogen had completely lost its light—it was now quite dark, without any sensible glow. It retained its very dark russet brown colour.

(e) Before the vessel was opened, while the radium was bright in hydrogen its radio-active power was measured with an electroscope; after it had been removed from the hydrogen and had become dark and glowless, its radio-activity was again measured. The amount of the induced leak of the charged leaves was found to be the same as before, showing that the sudden change from a bright condition to one without any sensible glow had not been accompanied by an alteration in the intensity of the β and γ rays.

(f) The glowless radium was examined in the dark at intervals of a few days. By May 9, 1905, a very faint glowing was perceived, and at the same time the dark brown colour was observed to have become less intense. These changes proceeded slowly until, by August 13, the radium had regained its original creamy colour and nearly its original brightness. During these three months its radiation, as measured by the electroscope, remained the same.

Experiment 2.—Fortunately we have for the purpose of comparison a

portion of the French radium which has been sealed up in hydrogen at reduced pressure since September 12, 1904, about 11 months. Many photographs of the spectrum of this sealed-up radium have been taken at intervals from last September to the present time, showing, with similar exposures, increasing feebleness, but always, when any action could be detected upon the plate, some of the stronger bands of the nitrogen spectrum. Recently, however, a band has appeared in the green part of the spectrum, for which the plate is but feebly sensitive, without any action being discernible on the plate in the blue and violet regions, for which the photographic film is greatly more sensitive. Fortunately on one plate the chief bands of the nitrogen spectrum, though excessively faint, can be just detected, while at the same time the new band, falling in a much less sensitive region photographically, is relatively strong.

The defined line which begins the band on the less refrangible side is a little more refrangible than the brighter edge of the green band of the Swan spectrum at $\lambda 5165$. The band has not yet been identified.

The band is accompanied by a faint continuous spectrum which runs back to D.

The radium bromide has turned to a dark russet brown colour, as in the former experiment. To the eye the brightness of the radium has remained greatly diminished, until within the last few days, when we suspect that, as in the preceding experiment, a slow increase of brightness has set in.

On re-examining all the photographs of the spectrum of the glow of radium which we have taken, a plate was found, developed on August 23, 1904, of the spectrum of a portion of the French radium which had been sealed up in hydrogen for a few days only, but when its light had faded to about one-half, which shows very faintly, but unmistakably, the new band.

The suggestion presents itself to the mind whether in both experiments when the radium had almost ceased to glow with nitrogen light, it was able to stimulate the molecules of the substance producing the band into luminescence. On this supposition an explanation of the sudden going out of the bright glow when the radium was taken out of the atmosphere of hydrogen in the first experiment would be found in the absence in the atmosphere of the needful molecules, the radium having lost temporarily the power of exciting nitrogen, unless we take the view that, to be stimulated into luminescence, nitrogen must be not merely in outward contact with the radium, but in a more intimate connection with it, which time is required to bring about.

The suggestion was considered in a former paper whether the operative cause of the glow was to be found in the β rays, which are known to be analogous to the cathode corpuscles, upon the nitrogen of the air. In these recent experiments the electroscope showed that these rays, and the γ rays,

were being radiated with undiminished force at the time that the radium bromide remained glowless in air. It may be mentioned here that the cathode discharge is efficient in bringing out easily the first spectrum of hydrogen,* but the radiations of radium appear to be unable to do this. Our experiments seem rather to support the view, suggested in our first paper, that the spontaneous light of radium may not be produced by any form of its radiations acting upon the nitrogen of the air outside it, but by a more direct action, through encounters with nitrogen molecules, in some way associated with the radium, of those molecules of the radium which are undergoing active changes.

ON THE SPECTRUM OF THE SPONTANEOUS LUMINOUS RADIATION OF RADIUM. PART IV.—EXTENSION OF THE GLOW

(From *Proc. Roy. Soc.*, lxxvii., p. 130, 1905)

IN our second paper† we suggest “whether the β rays, which are analogous to the cathode corpuscles, may not be mainly operative in exciting the radium glow. On this surmise it would be reasonable to expect some little extension of the glow outside the limit of the solid radium itself. We are unable to detect any halo of luminosity outside the limit of the solid radium bromide; the glow appears to end with sudden abruptness at the boundary surface of the radium.” We omitted to state that this conclusion was arrived at by eye-observations. The radium was observed in the dark with a lens, and with a low-power microscope.

The earlier photographs of the spectrum of the glow were taken, for the purpose of comparison spectra, with the height of the slit reduced by shutters so as to be within the width of the exposed radium bromide, and, therefore, these photographs would not show whether the bright bands of nitrogen extend into the air beyond the radium. Subsequently photographs were taken with the whole height of the slit, and on these we find that all the bands of nitrogen do extend to some little distance outside the radium salt. Our attention at the time being directed to other phenomena of the glow, we did not examine the photographs to see if the nitrogen bands extended beyond the radium.

In a paper, dated August 22, 1905, F. Himstedt and G. Meyer‡ state that in their photographs of the spectrum of RaBr_2 , the four nitrogen bands, 3577, 3371, about 3300, and 3159, extend beyond the radium salt, while the other less refrangible bands are not traceable outside the radium. In our photographs

* Liveing, *Proc. Camb. Phil. Soc.*, vol. xii., p. 337.

† *Proc. Roy. Soc.*, vol. lxxii., p. 410 (1903).

‡ F. Himstedt and G. Meyer, *Ber. d. Nat. Gesells. Freiburg*, vol. xvi., pp. 13–17.

all the nitrogen bands project beyond the radium salt ; the relative distance to which the extension can be detected in the case of each band being, as might be expected, in proportion to the strength of the impression of that band upon the photographic plate.

B. Walter and R. Pohl, in a paper dated September 1905,* give an account of experiments made with the help of screens, which show that for a distance of up to about 2 cm., the air surrounding radium bromide has an action on a photographic plate.

On re-examining an early photograph, taken in 1903 for another purpose, which is described in our second paper,† in which the RaBr_2 was enclosed in a very narrow tube of thin glass, we find that the bands of nitrogen, which are strong within the tube, show no trace of extension on the plate beyond the tube. This exposure of this plate was seven days.

This experiment, which we have repeated recently with an exposure of 14 days, shows that the luminosity of nitrogen in the near neighbourhood of radium bromide is not due to the cathode-like β -radiation, for this passes freely through glass.

Two explanations may be suggested : first, that the active cause is the α rays;‡ or secondly, that the nitrogen molecules which encounter those molecules of the radium which are undergoing active changes are broken up into ions, which are projected outwards, and give rise to the glow of luminous nitrogen.§

HISTORICAL NOTE

It seems to me desirable to put on record that about 1870 I had a large electro-magnet made by Mr. Ladd for the purpose of observing the lines of spectra in a strong magnetic field. I strongly suspected that modifications of the spectral lines would be seen.

My observations did not meet with success ; to some extent on account of an insufficiently strong magnetic field, but mainly, I believe, because I did not use a spectroscope of sufficient power.

These modifications of the lines are now known as the "Zeemann-effect," from the name of their discoverer in 1896.

* B. Walter and R. Pohl, *Ann. d. Phys.*, vol. xviii., p. 406.

† *Proc. Roy. Soc.*, vol. lxxii., p. 412.

‡ B. Walter, July 1905, showed by means of absorption screens that the radiation from radio-tellurium can produce the ultra-violet light of nitrogen (*Ann. d. Phys.*, vol. xvii., p. 367).

§ The experiments described in our last paper showed that probably the β rays are not the operative cause of the nitrogen glow (*Proc. Roy. Soc.*, vol. lxxvi., p. 488).

Section X
MISCELLANEOUS

LIST OF PAPERS

- “ Prismatic Examination of Microscopic Objects.” (First Application of the Spectroscope to the Microscope.)
Quart. Journ. Micros. Soc., 1865, No. xix., p. 85. 1865. P. 463.
- “ Binocular Vision.”
Astronomical Register, 1866. P. 465.
- “ On the Stars within the Trapezium of the Nebula of Orion.”
Month. Notices, vol. xxvi., p. 71.
- “ Note on the Heat of the Stars.”
Proc. Roy. Soc., vol. xvii., p. 309. 1869. P. 469.
- “ On the Function of the Sound-post, and on the Proportional Thickness of the Strings of the Violin.”
Proc. Roy. Soc., vol. xxxv., p. 241. 1883. P. 472.

NOTE ON THE PRISMATIC EXAMINATION OF MICROSCOPIC OBJECTS

(From *Quart. Journ. Micros. Soc.*, vol. xix., p. 85, 1865)

IT has long been in my mind that microscopical science might possibly receive some assistance from prismatic analysis. Other investigations on which I am engaged have prevented me from making experiments in this field of inquiry. Since, however, the plan which I had proposed to myself, and which I have adopted with success in a few preliminary trials, differs essentially from the arrangement of prismatic apparatus recently introduced by Mr. Sorby,* a short account of my method of observing may not be without interest to the Microscopical Society.

Microscopical science can scarcely hope for the same help from prismatic analysis which astronomy and chemistry have recently received, because the objects of investigation by the microscope are not self-luminous, as are the stars and terrestrial flames. The microscopist can hope to profit by the use of the prism in the case alone of those substances which modify by a special absorption the light by which they are rendered visible, either during transmission or reflection. The discoveries, however, of Professor Stokes in connection with the peculiar optical characters of blood and chlorophyll show that even this restricted field of investigation is one of considerable promise.

By means of the apparatus described below, the spectrum of any part of a microscopic object can be examined apart, and also can be compared with the spectra of the adjoining portions of the object.

In this manner the spectrum of a single blood-disk, or the spectrum of the contents of a single cell, can be observed, and any changes in living tissues which cause a modification of the spectrum can be watched and investigated.

Possibly microscopical physiology may receive some aid from this way of using the prism, since the deepest object-glasses, even the $\frac{1}{25}$ and $\frac{1}{50}$, may be employed.

* Mr. Sorby's plan was simply to view the object illuminated by a spectrum thrown upon the stage by a prism placed below it.

This method of prismatic observation is equally suited to an examination of the light reflected from different parts of an opaque object.

Essentially the plan consists in arranging the slit of an ordinary spectrum apparatus in the place of the eyepiece of the microscope.

The spectrum apparatus may be of any form, may be supported on a separate stand, or be made to form part of the microscope.

Behind the object-glass, at a distance of 3 or 4 inches, or at the place of the eyepiece, when removed, an adjustable slit (*a*) is placed; the object-glass is focussed upon the object on the stage so that its magnified image falls precisely upon the slit. The opening of the slit, which may be from $\frac{1}{200}$ th to $\frac{1}{400}$ th of an inch, allows the light of a small part only of this image to pass on to the prisms. If desired, this part of the object may be further reduced by shortening the length of the slit. It is obvious that, by the usual stage adjust-

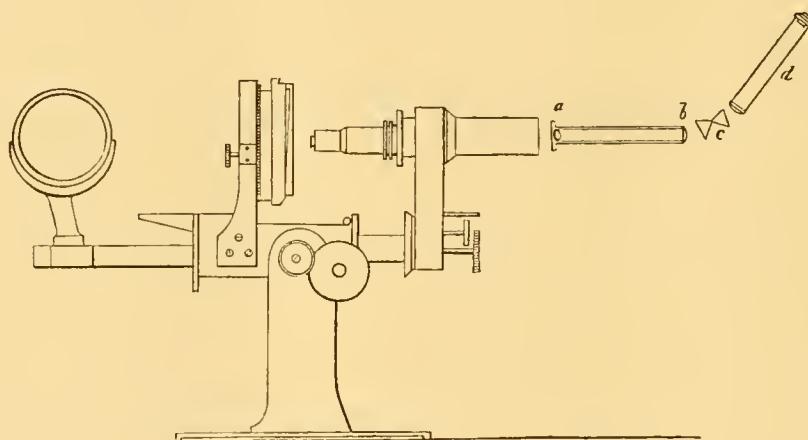


Fig. 54.

ments, any portion of the object can be made to fall within the jaws of the slit and to form a separate spectrum. (See diagram.)

Behind the slit, at its own focal distance, is placed an achromatic lens (*b*). The pencils emerge parallel, and then pass through one or more prisms (*c*). The pencils are then received by a small achromatic telescope (*d*), with which the spectrum is viewed.

The eyepiece of this telescope is adjusted so that the lines of Fraunhofer in solar light, or the sodium line in an artificial light from a source containing sodium, are well defined. The object-glass of the microscope is then to be moved towards or from the object on the stage until the longitudinal lines and bars of different intensity, due to the darker and lighter parts of the object, are sharply defined in the little telescope at the same time as the lines of Fraunhofer or the double line of sodium.

BINOCULAR VISION

(From *The Astronomical Register*, 1866)

SIR,—

The question raised by your correspondent Mr. C. S. Harris, in the last number of the *Register*, is one of considerable interest, and also possibly of some importance to observational astronomy.

The successful application of binocular vision to the microscope has not only added greatly to the pleasure of using that instrument, but in many instances, in the case of objects possessing a complex structure, vision with both eyes enables the observer to understand at a glance the relative positions and interdependence of the parts of the object.

Shortly after my friend Mr. Wenham's great success in enabling observers to use both eyes with so much advantage in microscopic work, I had several conversations with him about the practicability of applying to the astronomical telescope a similar method of obtaining binocular vision—namely, by halving, by means of a prism placed near the focal point, the pencils from the object-glass, so that each eye receives those of one-half of the object-glass. Several promising modifications of this method were discussed by us, but, unfortunately for observers with the telescope, Mr. Wenham's inventions for the improvement of the steam-engine and of the gas-engine have prevented him from carrying into execution any of the plans which he had devised.

It is evident that the only perfect method of observing distant objects with both eyes is to make use of two telescopes of equal aperture and magnifying power, placed side by side.

Besides the great drawback (at least, to most observers) of the expense of a second telescope, this plan, unless an arrangement of prisms be added for altering the direction of the pencils, does not permit the diameter of the object-glasses of the telescopes to exceed the distance between the pupils of the eyes of the observer. The late Mr. A. Ross fitted up in this manner two very fine telescopes of about 3 inches aperture. This instrument gave delightful vision of terrestrial objects and of the moon and planets.

I remember that Mr. Wenham suggested to me that two telescopes of large aperture, if of the Newtonian form of construction, might be conveniently combined by fitting right-angled prisms to the eye-tubes. The prisms would reflect the pencils from the two telescopes into the eyes of an observer stationed between them. Mr. Wenham was anticipated in this idea by a gentleman who successfully constructed a binocular Newtonian instrument, which had specula $6\frac{1}{4}$ inches in diameter. Some of your readers will remember that this instrument was advertised for sale in the early numbers of the *Register*.

Mr. Dawes, with whom I was in correspondence on the subject in 1861, wrote to me an interesting account of his experience of binocular vision. I have his permission to give the following extracts from his letter of March 27, 1861 :

" My own experience in binocular telescopes is confined to a careful experiment which I made a few years ago with two very excellent portable telescopes by Dollond, whose qualities and magnifying powers were almost exactly the same.

" With these nicely adjusted on a frame so as readily to produce a single image, I scrutinised various test-objects, such as fine engravings, etc., placed at accessible distances, so that I could easily compare what was visible through one or both of the telescopes with the appearances of the same object with the naked eye at the distance of a few inches. The *first impression* was really surprising: the object appeared so much larger, closer, and brighter. But I was greatly astonished to find that in the still more important effect of making out the minute details of an object difficult to define, the two telescopes and the two eyes seemed to have scarcely any superiority over one! And, indeed, I at last came to the conclusion that there was *none at all*. I have often since been struck with a similar effect in the use of a good binocular opera-glass. The effect is far more *agreeable*, and small points of light are brought out more clear and bright; and yet the features of the moon, for instance, are not really more *distinct* than with *one* of the glasses only. Whether such would be the conclusion arrived at by others, I know not; I think it might possibly be otherwise; but, at all events, I consider the subject of producing binocular vision with large telescopes extremely interesting. . . .

" It has occurred to me that an experiment might be made for deciding the probable advantage of binocular vision with a large telescope, by applying a complete achromatic microscope of low power, with a binocular eyepiece, as an eyepiece to the telescope. Taking 10 inches as the distance at which an ordinary eye can distinctly examine an object, your telescope would give a power of 12 times without any eyepiece. Then a microscope magnifying the diameter 20 times would produce a power of 240 times—quite sufficient for trying its effect upon planets and portions of the moon. A binocular achromatic microscope may not form one of the best eyepieces; yet I do not see why it should be a very bad one."

In accordance with Mr. Dawes' excellent suggestion, Mr. Ross made for me a simple clamp, by which I can attach the binocular body of one of his largest microscopes to the eye end of my achromatic telescope of 8 inches aperture and 10 feet focal length. The 3-inch, 2-inch, and 1-inch microscopic object-glasses answer admirably. Vision obtained in this way with both eyes is very agreeable, and may be continued for a considerable time without the feeling of fatigue. The rugged lunar surface, the strangely configurated cloudy

disk of Jupiter, and Saturn surrounded with his rings, are perhaps the objects which afford most pleasure to an observer using both eyes. It would be an observation of much interest, with a binocular instrument of large aperture, to watch the passage of the moon before a planet when an occultation occurs, and also to examine the phenomena usually attending a total solar eclipse. However, I agree with Mr. Dawes that binocular vision has no superiority over vision with one eye for the minute and careful scrutiny of difficult objects. The only instance in which I perceived any advantage from its use with my telescope was in the examination of the head of the Comet II, 1862. The true direction of the fan-like brush of light from the nucleus was remarkably well brought out when both eyes were used.

It may be that, in a few rare instances, binocular vision will be found of service to observational astronomy.

It is scarcely necessary to say that all observations in which measures have to be taken must continue to be made with one eye.

For several reasons I am of opinion that the best method of obtaining binocular vision with achromatic telescopes will be found to be by the employment of a modified form of Mr. Wenham's prism.

Yours obediently,

WILLIAM HUGGINS.

UPPER TULSE HILL, S.W., Jan. 10, 1866.

Sir,—

In my letter on Binocular Vision with the telescope, printed in the February number of the *Register*, it was my intention to speak only of vision with both eyes. I endeavoured carefully to avoid making any reference to "stereoscopic effect." As, however, my friend Capt. Noble appears to have misunderstood me in reference to this matter, you will permit me, perhaps, to add the remarks which follow as a postscript to my letter.

Since the pencils which reach the earth from celestial objects are sensibly parallel, it is obvious that, with the very limited distance which exists between the halves of a large object-glass divided by a suitable prism, or the separate object-glasses of a binocular instrument, no sensible dissimilarity between the images will be obtained.

If we may receive the statement of Dr. Kitchiner, in his time "the difficulty of obtaining large object-glasses induced them to make binocular telescopes. M. Aubert had one composed of two 5-foot achromatics, each having an aperture of 3 inches."

It was soon found that arming the second eye with a telescope of similar power to that furnished to the other, does not double the luminous impression conveyed to the observer. Dr. Kitchiner states that Dr. Irwin, after a variety

of experiments, came to the conclusion that objects seen with both eyes appear only one-thirteenth part brighter than when seen with only one eye; also, that Mr. George Dollond, and Dr. Firminger an observer at the Royal Observatory, considered that objects viewed with a binocular telescope appear brighter than when only one telescope is used, in the proportion of 3 to 2.

Mr. Dawes' excellent observations, which are given in my former letter, prove that the employment of a second telescope does not increase the observer's power of making out the minute details of an object.

It will be, nevertheless, in accordance, I believe, with the experience of most persons, that binocular vision is much more agreeable than the use of one eye, and especially is this the case when an observation is of long duration. I have little doubt that, if we could only see *as well* with binocular telescopes, we should greatly prefer them. One reason may be that few of us know what to do with the eye which is not in use. Polyphemus would have made an excellent observer. It is frequently very inconvenient to place the hand before the unemployed eye if it remains open, or in any other way to screen it completely from surrounding objects. In my own case, I find it to be impossible to close the eyelids of one eye without in a slight degree impairing the vision of the other. The experiment may be made in this way: Place the hand over one eye, and look with the other at a bright point of light—for example, a street lamp on a dark night, at a distance of two or three hundred feet; carefully notice the number and length of the rays which will appear to stream from it, then remove the hand from the other eye, and close it. I always find, under such circumstances, that the vision of the bright point is less perfect.

Most observers will, I believe, admit that, even when the images received by the two eyes are not sensibly dissimilar, as is the case of those of celestial objects, a very agreeable "stereoscopic effect" is frequently produced. This stereoscopic appearance will probably be observed whenever the images are of objects which are suitable for the suggestion to the mind of solidity or relief. As an example of the power of suggestion, may be mentioned the well-known experiment of causing a single photographic picture to appear strongly "stereoscopic" by viewing it with one eye through a small tube which cuts off from view all other objects.

By applying the binocular microscope as an eyepiece to the telescope, I have seen the craters on the moon, Saturn, etc., appear in strong relief.

Whether the effect of the suggestions to the mind caused by the combination of two similar images may be in any case to give a *truer* conception of the form of a distant object, I am not prepared to say. In the instance referred to in my former letter—that of the observation of Comet II, 1862—I thought that I received new information from using both eyes.

In the *Monthly Notices* for November 1864, at page 22, Mr. John Watson says: ". . . On applying it (a binocular Herschelian telescope) to the moon, I distinctly saw black lines or rills with both eyes, which had escaped my notice with either eye when used separately. . . . I may add, that I found it to be much more pleasant to observe with both eyes than with one, and less fatiguing."

The study of the effect of the combination of similar images may be conveniently made with a new binocular microscope recently invented by Messrs. Powell & Lealand. In this instrument each eye has the advantage of the full aperture of the object-glass, and the images are similar. In the present form of this instrument, one of the images is not so bright as the other.

I am aware that several of the matters referred to in this letter are connected with prolonged physiological and metaphysical controversies (see T. K. Abbott's *Sight and Touch*, 1864). I may say, therefore, that I have no wish to write further on this subject at present.

Yours obediently,

WILLIAM HUGGINS.

UPPER TULSE HILL, March 14, 1866.

NOTE ON THE HEAT OF THE STARS

(From *Proc. Roy. Soc.*, vol. xvii., p. 309. 1869)

IN the summer of 1866 it occurred to me that the heat received on the earth from the stars might possibly be more easily detected than the solar heat reflected from the moon. Mr. Becker (of Messrs. Elliott Brothers) prepared for me several thermopiles, and a very sensitive galvanometer. Towards the close of that year, and during the early part of 1867, I made numerous observations on the moon, and on three or four fixed stars. I succeeded in obtaining trustworthy indications of stellar heat in the case of the stars Sirius, Pollux, and Regulus, though I was not able to make any quantitative estimate of their calorific power.

As I had the intention of making these observations more complete, and of extending them to other stars, I have refrained hitherto from making them known. I find, however, that I cannot hope to take up these researches again for some months, and therefore venture to submit the observations in their present incomplete form.

An astatic galvanometer was used, over the upper needle of which a small concave mirror was fixed, by which the image of the flame of a lamp could be thrown upon a scale placed at some distance. Usually, however,

I preferred to observe the needle directly by means of a lens so placed that the divisions on the card were magnified, and could be read by the observer when at a little distance from the instrument. The sensitiveness of the instrument was made as great as possible by a very careful adjustment from time to time of the magnetic power of the needles. The extreme delicacy of the instrument was found to be more permanently preserved when the needles were placed at right angles to the magnetic meridian during the time that the instrument was not in use. The great sensitiveness of this instrument was shown by the needles turning through 90° when two pieces of wire of different kinds of copper were held between the finger and thumb. For the stars, the images of which in the telescope are points of light, the thermopiles consisted of one or of two pairs of elements; a large pile, containing twenty-four pairs of elements, was also used for the moon. A few of the later observations were made with a pile of which the elements consist of alloys of bismuth and antimony.

The thermopile was attached to a refractor of 8 inches aperture. I

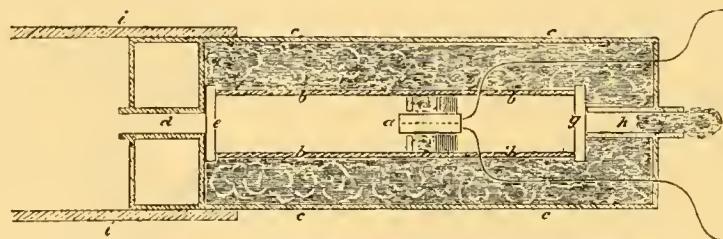


Fig. 55.

considered that though some of the heat-rays would not be transmitted by the glass, yet the more uniform temperature of the air within the telescope, and some other circumstances, would make the difficulty of preserving the pile from extraneous influences less formidable than if a reflector were used.

The pile *a* was placed within a tube of cardboard, *b*; this was enclosed in a much larger tube formed of sheets of brown paper pasted over each other, *c*. The space between the two tubes was filled with cotton-wool. At about 5 inches in front of the surface of the pile, a glass plate (*e*) was placed for the purpose of intercepting any heat that might be radiated from the inside of the telescope. This glass plate was protected by a double tube of cardboard, the inner one of which (*d*) was about half an inch in diameter. The back of the pile was protected in a similar way by a glass plate (*g*). The small inner tube (*h*) beyond the plate was kept plugged with cotton-wool; this plug was removed when it was required to warm the back of the pile, which was done by allowing the heat radiated from a candle-flame to pass through the tube to the pile. The apparatus was kept at a distance of about

2 inches from the brass tube by which it was attached to the telescope by three pieces of wood (*i*), for the purpose of cutting off as much as possible any connection by conduction with the tube of the telescope.

The wires connecting the pile with the galvanometer, which had to be placed at some distance to preserve it from the influence of the ironwork of the telescope, were covered with gutta-percha, over which cotton-wool was placed, and the whole wrapped round with strips of brown paper. The binding-screws of the galvanometer were enclosed in a small cylinder of sheet gutta-percha, and filled with cotton-wool. These precautions were necessary, as the approach of the hand to one of the binding-screws, or even the impact upon it of the cooler air entering the observatory, was sufficient to produce a deviation of the needle greater than was to be expected from the stars.

The apparatus was fixed to the telescope so that the surface of the thermopile would be at the focal point of the object-glass. The apparatus was allowed to remain attached to the telescope for hours, or sometimes for days, the wires being in connection with the galvanometer, until the heat had become uniformly distributed within the apparatus containing the pile, and the needle remained at zero, or was steadily deflected to the extent of a degree or two from zero.

When observations were to be made, the shutter of the dome was opened, and the telescope, by means of the finder, was directed to a part of the sky near the star to be examined where there were no bright stars. In this state of things the needle was watched, and if in four or five minutes no deviation of the needle had taken place, then by means of the finder the telescope was moved the small distance necessary to bring the image of the star exactly upon the face of the pile, which could be ascertained by the position of the star as seen in the finder. The image of the star was kept upon the small pile by means of the clock-motion attached to the telescope. The needle was then watched during five minutes or longer; almost always the needle began to move as soon as the image of the star fell upon it. The telescope was then moved, so as to direct it again to the sky near the star. Generally, in one or two minutes, the needle began to return towards its original position.

In a similar manner twelve to twenty observations of the same star were made. These observations were repeated on other nights.

The mean of a number of observations of Sirius, which did not differ greatly from each other, gives a deflection of 2° .

The observations of Pollux $1\frac{1}{2}^\circ$.

No effect was produced on the needle by Castor.

Regulus gave a deflection of 3° .

In one observation Arcturus deflected the needle 3° in 15 minutes.

The observations of the full moon were not accordant. On one night a

sensible effect was shown by the needle; but at another time the indications of heat were excessively small, and not sufficiently uniform to be trustworthy.

It should be stated that several times anomalous indications were observed, which were not traced to the disturbing cause.

The results are not strictly comparable, as it is not certain that the sensitiveness of the galvanometer was exactly the same in all the observations; still it was probably not greatly different.

Observations of the heat of the stars, if strictly comparable, might be of value, in connection with the spectra of their light, to help us to determine the condition of the matter from which the light was emitted in different stars.

I hope at a future time to resume this inquiry with a larger telescope, and to obtain some approximate value of the quantity of heat received at the earth from the brighter stars.

NOTE

(From *Atlas of Representative Stellar Spectra*, p. 88, footnote)

WITHOUT wishing to attach importance to that which may not be more than an accidental coincidence, it is worth while, perhaps, to point out that my early attempts to obtain indications of heat from the stars, by means of a very sensitive galvanometer (*Proc. Roy. Soc.*, vol. xvii., p. 309), agree with the recent determinations of stellar heat radiations at the Yerkes Observatory, by Professor E. F. Nichols, with an extremely sensitive radiometer of his own construction (*Astrophys. Journ.*, vol. ix., p. 360, May 1899), in placing the heat radiation of the solar star, Arcturus, considerably above that of the brilliant white stars Vega and Sirius.

My experiments showed a deflection of 3° for Arcturus, and 2° only for Sirius. Professor Nichols' extremely sensitive apparatus makes the heat ratio of Arcturus to that of Vega, taking the mean of five nights' work, to be $2\cdot 1$.

It should be stated that the unsuccessful attempts of Professor Boys, with a very sensitive radiomicrometer in 1890 (*Proc. Roy. Soc.*, vol. xlvi., p. 480, 1890), seemed to show that my early results, with a less sensitive instrument, were probably not due really to stellar heat, but to some foreign cause.

ON THE FUNCTION OF THE SOUND-POST AND ON THE PROPORTIONAL THICKNESS OF THE STRINGS OF THE VIOLIN

(From *Proc. Roy. Soc.*, vol. xxxv., p. 241. 1883)

SIR JOHN HERSCHEL says: "It (the bridge) sets the wood of the upper face in a state of regular vibration, and this is communicated to the back through

a peg set up in the middle of the fiddle, and through its sides, called the 'soul' of the fiddle, or its sounding-post." *

Savart says : " L'âme a pour usage de transmettre au fond les vibrations de la table . . . son diamètre est déterminé par la qualité du son qu'on veut avoir ; il est maigre quand elle est trop mince, et sourd quand elle est trop grosse." †

Daguin, in his "Traité de Physique," devotes a whole page to the discussion of the functions of the sound-post. The most important sentences are the following : ". . . L'âme n'agit pas comme conducteur du son. . . Il nous semble que l'on doit expliquer l'effet de l'âme de la manière qui suit. L'âme, ou les pressions extérieures par lesquelles on la remplace, a pour effet de donner au pied du chevalet un point d'appui autour duquel il vibre en battant sur la table de son autre pied. Si l'un des pieds n'était appuyé sur un point fixe, il se relevait pendant que l'autre s'abaissait, parce que les cordes n'agissent pas normalement à la table, puisque l'archet les ébranle très obliquement, ce qui entraîne le chevalet dans un mouvement transversal quand il n'a pas de point d'appui fixe. Lorsque l'archet est dirigé normalement aux tables, cet inconvénient n'existe plus, et l'âme n'est plus nécessaire." ‡

Helmholtz says : " The vibrating strings of the violin, in the first place, agitate the bridge over which they are stretched. This stands on two feet over the most mobile part of the belly between the two 'f' holes. One foot of the bridge rests upon a comparatively firm support—namely, the sound-post, which is a solid rod inserted between the two plates, back and belly, of the instrument. It is only the other leg which agitates the elastic wooden plates, and through them the included mass of air." §

The experiments || which follow have been made for the purpose of ascertaining whether it be any part of the function of the sound-post to convey vibrations to the back, or whether this post acts solely as a prop supporting the belly, so that its elasticity is not injured by the pressure from the strings, and also, as Daguin states, affords the firm basis which he considers necessary for one foot of the bridge.

Mr. Hill, and other practical men, maintain that the quality of the wood of which the sound-post is made affects the tone of the violin, as undoubtedly do very minute differences of position. If the quality of the wood is important, we must admit that vibrations are conveyed by the post.

* "Encyclopædia Metropolitana," Article "Sound," p. 804.

† "Mémoire sur la Construction des Instruments à Cordes et à Archet," 8vo., Paris, 1819. Also Biot's "Report," *Ann. de Chimie*, tome xii., pp. 225-255.

‡ "Traité de Physique Acoustique," tome i., p. 575.

§ "Sensations of Tone," translated by Ellis, p. 137. In the fourth German edition this passage remains unaltered.

|| I wish to express my indebtedness to Mr. A. J. Ellis, F.R.S., for some suggestions in connection with these experiments.

Whether or not the sound-post exercises the function of transmitting vibrations, it is obvious (1) that it performs the important duty of contributing to the support of the belly; (2) that the nodal arrangement of the belly, and also that of the back, are influenced by the pressure of the ends of the post against the upper and lower plates; (3) that Helmholtz is right, at least so far that the leg of the bridge under the 4th or G string has much more power than the other, in setting the belly into vibration.

The usual way of investigating vibrations by the scattering of sand over the surface of the agitated body is difficult of application to the violin, on account of the curved form of the upper and lower plates. I found a convenient method to be by the use of what I may call a touch-rod. It consists of a small round stick of straight-grained deal a few inches long; the forefinger is placed on one end, and the other end is put lightly in contact with the vibrating surface. The finger soon becomes very sensitive to small differences of agitation transmitted by the rod.

The experiments were made on a strongly made modern violin, and in some cases repeated on a fine violin by Stradivarius in the possession of the writer.

The sand method, and also the touch-rod, showed that the position of maximum vibration of the belly is close to the foot of the bridge under the 4th or G string. The place of least vibration is exactly over the top of the sound-post behind the other foot of the bridge. The back is strongly agitated, the vibrations being least powerfully felt where the sound-post rests, which is at nearly the thickest part of the back. These effects were very satisfactorily observed on a violoncello, where the phenomena are on a larger scale.

When the sound-post was removed from the violin, the large difference of the amount of vibration on the two sides of the belly was no longer present, the belly was about equally strongly agitated on both sides, making allowance for the string which was bowed. The tone became very poor and thin, as is well known to be the case when the sound-post is removed. The vibration of the back was now very feeble, as compared with its vibration when the sound-post was present—a circumstance in favour of the view that the sound-post conveys vibrations to the back.

A clamp of wood was prepared which could be so placed on the violin, as to connect by an arch of wood outside the violin the place of the belly behind the bridge where the top of the sound-post presses, with the place of the back where it rests. It was expected that the wooden arch would restore to some extent the connection of belly and back which was broken by the removal of the post, and carry, though imperfectly, vibrations from the upper plate to the back.

When this clamp was put on, the poor and thin sound was altered to the

fuller character of tone which belongs to the violin when the sound-post is in its place. On testing the condition of the back its normal state of vibration was found to be in a large degree restored. If, while the strings were being bowed, the clamp was suddenly removed, the tone at the same moment fell to its poor character, and the vibration of the back as instantly diminished.

It was further observed that if the upper part of the clamp pressed upon the belly without the lower part coming into contact with the back, the tone was altered in the same direction as when the sound-post was present, but it was not until the lower part of the clamp was in contact with the back that the normal character of the tone was fully restored. A similar effect to that resulting from the pressing of one end of the clamp only was produced by firmly placing one end of a wooden rod at this part of the belly. This effect may be due to the setting-up in the belly, by pressure at this part, of the peculiar nodal arrangement which the post produces when in its place.*

There could be no doubt that vibrations were carried by the clamp, for the lower end was powerfully agitated when the upper end rested upon the belly. If the sole function of the sound-post is to serve as a firm prop for the foot of the bridge, it should fulfil this condition most fully when placed under the foot of the bridge. In this position of the sound-post, however, as is well known, the tone is much injured.

In order to separate that part of the function of the sound-post which serves as a support from the further function it may possess as a transmitter of vibrations, it was desirable to introduce such alterations in the structure of the sound-post as would enable it to retain its supporting power, and yet greatly modify and, if possible, stop its power of transmitting vibrations. A sound-post was made in which about half an inch of the middle was cut out, and a piece of lead inserted, also a sound-post in which instead of lead sealing-wax was put in. The effect of these compound posts, which retained uninjured their prop power, was to modify greatly the quality of the tone, but not to diminish its quantity in any marked degree—a result in favour of the view that the character of the wood of which the post is made does influence the tone, and that vibration is transmitted by the post. As these compound posts could transmit vibrations freely, it was desirable to contrive a post which would not carry vibrations and yet form a firm prop. A post was made with a piece of hard india-rubber inserted in the middle, but this post was found by experiment with a tuning-fork to transmit vibrations to some extent. Other

* According to Daguin some similar experiments were made by Savart, but I have failed to find them in those of his papers to which I have had access.

"On peut la (l'âme) mettre en dehors, en l'appuyant à une espèce d'arcade dont on colle les pieds de chaque côté du violon. . . . On peut la remplacer par la pression d'un poids convenable appuyé sur la table supérieure. . . . Savart a conclu de là que l'âme a pour effet de rendre normales les vibrations de la table. . . ."—*Traité de Physique*, tome i., p. 575.

materials were tried without success. A post capped at each end with pieces of sheet vulcanised rubber stopped almost completely the sound of a tuning-fork when the foot of the fork rested on the rubber over one end of the post, while the other end equally protected with rubber rested on a body capable of reinforcing the sound of the fork. This rubber-capped post was firmly fixed in position in the violin, so that it would be able to support fairly well the belly and foot of the bridge, and yet not be able to carry vibrations; unfortunately it does not seem possible, from the nature of things, to have a *rigid* prop which does not transmit vibrations, but this post, with thin sheet rubber at the ends firmly forced into position, must have been fairly efficient in its supporting power. The effect on the tone was about the same as when the sound-post was removed. When the wooden clamp was put on, then the normal tone returned, and the back vibrated strongly.

These experiments appear to show that the sound-post is more than a prop, and that besides its other functions, it does transmit vibrations to the back in addition to those which are conveyed through the sides.

Experiments with sand and the touch-rod appear to me to show that Helmholtz's statement is too absolute when he says "it is only the other leg of the bridge which agitates the elastic wooden plates." Undoubtedly it is the 4th string foot of the bridge which is the more powerful in agitating the upper plate, but the other foot appears to me also to have an influence. When the post is placed exactly under the foot of the bridge, then the belly on this side is almost without vibration; if the post is absent, then this foot appears to agitate its own side of the belly as strongly as the other foot. As there is no post on the 4th string side of the fiddle, that foot stands in a position most favourable for setting up vibrations in the belly, being nearly half-way between the supports of the belly at the tail and the neck end of the violin. The other side of the belly, on the 1st string side, where the other foot of



Fig. 56.



Fig. 57.

the bridge rests, is divided into two parts by the damping effect of the end of the sound-post—namely, the part *a* and the part *b*. It is obvious that this foot of the bridge is unfavourably placed for setting the part of the belly, *b*, into vibration, since it is so far from its central mobile part. On the other hand, its position is favourable for a portion of its energy of vibration to be transmitted through the post to the back.

Practically very small differences of position of the top of the post behind

the foot of the bridge are found to alter largely the character of the tone of the fiddle, and in the case of fine instruments the setting of the post is an operation demanding much care and judgment. The explanation lies probably in the circumstance that a small difference in the position of the post will alter greatly the proportion of energy passing through the post to that which is absorbed into vibrations of this side of the belly. At the same time it must also alter slightly the nodal arrangement of the belly which must have an influence on the tone. If from the form of construction, or relative quality of the wood of the upper plate as compared with the under plate, the conditions of a violin are such that the highest quality of tone of which it is capable requires a relatively larger amplitude of vibration of the back, the position of the sound-post should be nearer the bridge. In a contrary condition of things the sound-post should be farther from the bridge. The extreme range needed in different violins is about a quarter of an inch. At the same time any shift of the post must affect the relative mobility of the two sides of the belly.

If the sound-post transmits vibrations, these will be in addition to those received from the sides of the violin. It may be, therefore, that one condition which determines the best position of the post is the degree in which from their form and material these fulfil this duty. All the sides must share in this duty, but the touch-rod shows that a large part of this action is borne by the parts of the sides which curve inwards under where the strings are bowed. It is in harmony with this view that Mr. Hill states, that if the inside blocks at the corners, which are put to strengthen these parts, extend in a small degree into these curved portions, the tone is injured.

The plane of the vibrations of the strings is that in which they are bowed, which is more or less oblique to the bridge. The vibrations may be considered divided into two sets at right angles to each other, α and β .

The touch-rod shows that these vibrations exist strongly in the upper part of the bridge. I venture to suggest that the use of the peculiar cutting of the bridge, which was finally fixed from trials by Stradivarius, is to sift the vibrations communicated by the strings, and to allow those only, or mainly, to pass to the feet, which would be efficient in setting the body of the instrument into vibration, the other vibrations which would be injurious in tending to give a transverse rocking motion to the bridge being for the most part absorbed by the greater elasticity given to the upper part of the bridge by the cutting. Below the two large lateral cuts the touch-rod shows

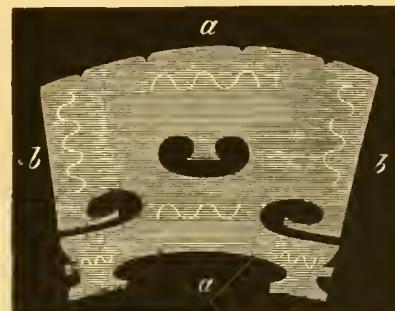


Fig. 58.

a very great falling off of the vibrations b . In the case of a violoncello these vibrations were also very greatly reduced below the side openings of the bridge.

The violin on which the experiments were made was without a bass bar, which is a piece of pine glued to the under side of the belly on the 4th string side. This bar is regarded as strengthening the belly, and also enabling it to respond better to the lower notes. The touch-rod showed no difference in the general behaviour of this violin, from a fine one by Stradivarius containing a bass bar.*

ON THE PROPORTIONAL THICKNESS OF THE STRINGS

As the lengths of the strings are the same, we have only the two conditions of weight and tension on which their pitch depends. It is obvious that for equal pressure on the feet of the bridge, as well as for more convenient fingering and bowing, the strings should be at the same tension. They should, therefore, differ in weight, so as to give fifths when brought to the same tension. The weights of the strings must be inversely as the squares of the number of vibrations, which in the case of fifths, is as 3 to 2, namely, as 9 to 4. As the first three strings are of the same material, it is more convenient to take their diameters, which must be as 3 to 2, that is, each string in advancing from the 1st string must be half as thick again as the string next to it. In the case of the 4th string covered with wire, we must find the weight of the 3rd string of gut, and take a 4th string of which the weight is 9 to 4 for the 3rd string.

A good average thickness of 2nd (A) string is 0.0355 inch. Then the strings should be—

$$\begin{aligned}1\text{st} &= 0.0237 \\2\text{nd} &= 0.0355 \\3\text{rd} &= 0.0532\end{aligned}$$

A gut string 0.0532 inch in diameter weighs, when of the same length as a 4th string, 0.98 grm., then the 4th = 2.20 grms.

Ruffini sells sets of strings in sealed boxes, and these were found to be in about the same relative proportion to each other as the sizes indicated on the gauges sold by several makers.

* In the "Early History of the Violin Family," Engel, speaking of the Crwth, says: "Furthermore, the contrivance of placing one foot of the bridge through the sound-hole, in order to cause the pressure of the strings to be resisted by the back of the instrument, instead of by the belly, is not so extraordinary and peculiar to the Crwth as most writers on Welsh music maintain. It may be seen on certain Oriental instruments of the fiddle kind which are not provided with a sound-post. For instance, the bridge is thus placed on the three-stringed fiddle of the modern Greek, which is only a variety of the ordinary rabáb, but which the Greeks call lyra. Inappropriate as the latter designation may appear, it is suggestive, inasmuch as it points to the ancient lyra as the progenitor of the fiddle."—P. 28.

The measures of a set of Ruffini's strings were found to be—

1st =	0·0265	inch.
2nd =	0·0355	"
3rd =	0·0460	"
4th =	1·4100	grm.

It will be seen that the 1st string is thicker, and the 3rd thinner, and the 4th much lighter than the theoretical values. Therefore the tension of the 1st string would be greater, and that of the 3rd and 4th strings less than they should be in relation to that of the 2nd string. The greater flexural rigidity of the 4th string will have a small effect in the direction of making the vibrations quicker, and therefore of making the tension required less.

By means of a mechanical contrivance I found the weights necessary to deflect the strings to the same amount when the violin was in tune. The results agreed with the tensions which the sizes of the strings showed they would require to give fifths.

A violin strung with strings of the theoretical size was very unsatisfactory in tone.

The explanation of this departure of the sizes of the strings which long experience has shown to be practically most suitable, from the values they should have from theory, lies probably in the circumstance that the height of the bridge is different for the different strings. It is obvious, where the bridge is high, there is a greater downward pressure. By this modification of the sizes of the strings there is not the greater pressure on the 4th string side of the bridge, which would otherwise be the case. On the contrary, the pressure is less, which may assist the setting of the belly into vibration. There is also the circumstance that the strings which go over a high part of the bridge stand farther from the finger-board, and have therefore to be pressed through a greater distance, which would require more force than is required for the other strings, if the tension were not less.

Section XI

LECTURES AND ADDRESSES

LIST OF SOME LECTURES

“Physical and Chemical Constitution of the Fixed Stars and Nebulæ.”
(Lecture.)

Proc. Roy. Inst., 1866, vol. iv., p. 441.

“Results of Spectrum Analysis applied to the Heavenly Bodies.” (Lecture.)
Report Brit. Assoc., 1866, p. 140. P. 485.

Also in book form, with illustrations and footnotes: “On the Results of Spectrum Analysis applied to the Heavenly Bodies.” (W. Ladd,
Beak Street, London, 1866.)

“Further Results of Spectrum Analysis applied to the Heavenly Bodies.”
(Lecture.)

Proc. Roy. Inst., vol. v., p. 475. 1869.

The Rede Lecture, Cambridge. 1869.

The Photographic Spectra of Stars.

Proc. Roy. Inst., vol. ix., p. 285. 1880.

“On Comets.” (Lecture.)

Proc. Roy. Inst., vol. x., p. 1. 1882.

“On the Solar Corona.” (Lecture.)

Proc. Roy. Inst., vol. xi., Part II., p. 202. 1885.

“Presidential Address, British Association for the Advancement of Science.”

Report Brit. Assoc., 1891, p. 1. P. 504.

"On the New Star in Nova Aurigæ." (Lecture.)
Proc. Roy. Inst., vol. xiii., p. 615. May, 1893.

"Presidential Addresses. The Royal Society, 1902, 1903, 1904 and 1905."
Reprinted with additions, "The Royal Society; or, Science in the State
and in the Schools." (Methuen & Co., 1906.)

NOTE

FROM my various Lectures I have selected for reprinting my Lecture before the British Association for the Advancement of Science, in 1866, which gave, for the first time, a full summary of my work, begun in 1856, up to that time; and my Address, as President, at the meeting of the Association at Cardiff in 1891, in which I gave a succinct account of the great development of the "New Astronomy" to that date.

A DISCOURSE ON SPECTRUM ANALYSIS APPLIED TO THE HEAVENLY BODIES

GIVEN IN THE THEATRE, NOTTINGHAM, ON AUGUST 24, 1866

(From the *Nottingham Daily Guardian*)

AN important invention or discovery seldom, if ever, remains sterile and alone. It gives birth to other discoveries. The telescope and the microscope have led to remarkable discoveries in Astronomy and in minute Anatomy and Physiology, which would not have been possible without those instruments. The observation that a magnetic body, free to move, arranges itself nearly north and south has not only contributed immensely to the extension of commerce and of geographical discovery, but also has founded the important science of terrestrial magnetism.

This evening I have to bring before you some additions to our knowledge in the department of Astronomy, which have followed from a comparatively recent discovery. The researches of Kirchhoff have placed in the hands of the astronomer a method of analysis which is specially suitable for the examination of the heavenly bodies. So unexpected and important are the results of the application of spectrum analysis to the objects in the heavens, that this method of observation may be said to have created a new and distinct branch of astronomical science.

Physical Astronomy, the imperishable and ever-growing monument to the

memory of Newton, may be described as the extension of terrestrial dynamics to the heavens. It seeks to explain the *movements* of the celestial bodies on the supposition of the universality of an attractive force similar to that which exists upon the earth.

The new branch of astronomical science which spectrum analysis may be said to have founded, has for its object to extend the laws of terrestrial physics to the other phenomena of the heavenly bodies, and it rests upon the now established fact that matter of a nature common to that of the earth, and subject to laws similar to those which prevail upon the earth, exists throughout the stellar universe.

The peculiar importance of Kirchhoff's discovery to *astronomy* becomes obvious, if we consider the position in which we stand to the heavenly bodies. Gravitation and the laws of our being do not permit us to leave the earth; it is therefore by means of *light alone* that we can obtain any knowledge of the grand array of worlds which surround us in cosmical space. The starlit heavens is the only chart of the universe we have, and in it each twinkling point is the sign of an immensely vast, though distant region of activity.

Hitherto the light from the heavenly bodies, even when collected by the largest telescopes, has conveyed to us but very meagre information, and in some cases only of their form, their size, and their colour. The discovery of Kirchhoff enables us to interpret symbols and indications hidden within the light itself, which furnish trustworthy information of the chemical, and also to some extent of the physical condition of the excessively remote bodies from which the light has emanated.

We are indebted to Newton for the knowledge that the beautiful tints of the rainbow are the common and necessary ingredients of ordinary light. He found that when white light is made to pass through a prism of glass it is decomposed into the beautiful colours which are seen in the rainbow. These colours, when they are in this way separated from each other, form the *Spectrum* of the light. Let this white plate represent the transverse section of a beam of white light travelling towards you. Let now a prism be interposed in its path. The beam of white light is not turned aside as a whole, but the coloured lights composing it are deflected differently, each in proportion to the rapidity of its vibrations. An obvious consequence will be that on emerging from the prism the coloured lights which formed the white light separate from each other, and in place of the white light which entered the prism we have *its Spectrum*, that is, the *coloured lights which composed it, in a state of separation from each other*. Wollaston and Fraunhofer discovered that when the light of the sun is decomposed by a prism, the rainbow colours which form its spectrum are not continuous, but are interrupted by a large number of dark lines. These lines of darkness are the symbols which indicate

the chemical constitution of the sun. It was not until recently, in the year 1859, that Kirchhoff taught us the true nature of these lines. He himself immediately applied his method of interpretation to the dark lines of the solar spectrum, and was rewarded by the discovery that several of the chemical elements which exist upon the earth are present in the solar atmosphere.

It is my intention to bring before you this evening the results of the extension of this method of analysis to the heavenly bodies other than the sun. These researches have been carried on in my observatory during the last four years. In respect of a large part of these investigations, viz. those of the moon, the planets, and fixed stars, I have had the great pleasure of working conjointly with my friend, the very distinguished chemist and philosopher Dr. Wm. A. Miller. Fifty years ago Fraunhofer recognised several of the solar lines in the spectra of the moon, Venus, Mars, and some stars. Recently Donati, Janssen, Secchi, Rutherford, and the Astronomer Royal, have observed lines in some stars. Before I describe the results of our observations, I will state, in a few words, the principles of spectrum analysis upon which our interpretation of the phenomena we have observed has been based, and also the method of observing which we have employed.

When light which has emanated from different sources is decomposed by a prism, the spectra which are obtained may differ in several important respects from each other. All the spectra which may present themselves can be conveniently arranged in three general groups. A spectrum illustrating each of these three orders is placed upon the diagram.

1. The special character which distinguishes spectra of the *first order* consists in that the continuity of the coloured band is unbroken either by dark or bright lines. By means of the electric lamp, Mr. Ladd will throw a spectrum of this order upon the screen. We learn from such a spectrum that the light has been emitted by an opaque body, and almost certainly by matter in the solid or liquid state. A spectrum of this order gives to us no knowledge of the chemical nature of the incandescent body from which the light comes. In the present case, the light is emitted by the white-hot carbon points of the electric lamp. A spectrum in all respects similar would be formed by the light from incandescent iron, or lime, or magnesia.

2. Spectra of the *second order* are very different. These consist of coloured lines of light separated from each other. From such a spectrum we may learn much. It informs us that the luminous matter from which the light has come is in the *state of gas*. It is only when a luminous body is free from the molecular trammels of solidity and liquidity that it can exhibit its own peculiar power of radiating certain coloured rays alone. Hence substances *when in a state of gas* may be distinguished from each other by their spectra. Each element, and every compound body that can become luminous in the gaseous state

without suffering decomposition, is distinguished by a group of lines peculiar to itself. These green lines are produced by silver in the state of gas, and only by silver gas. It is obvious that if the groups of lines characterising the different terrestrial substances be known, a comparison of these as standard spectra, with the spectrum of light from an unknown source, will show whether any of these terrestrial substances exist in the source of the light.

3. The *third order* consists of the spectra of incandescent solid or liquid bodies, in which the continuity of the coloured light is broken by dark lines. These dark spaces are not produced by the source of the light. They tell us of vapours through which the light has passed on its way, and which have robbed the light by absorption of certain definite colours or rates of vibration; such spectra are formed by the light of the sun and stars.

Kirchhoff has shown that if vapours of terrestrial substances come between the eye and an incandescent body, they cause groups of dark lines, and further, that the *group of dark lines* produced by each vapour is identical in the number of lines, and in their positions in the spectrum, with the *group of bright lines* of which the light of the vapour consists when it is luminous.

Mr. Ladd will throw upon the screen the spectrum of incandescent carbon points which contain sodium. Observe in addition to the continuous spectrum of the incandescent carbon a bright yellow band, which indicates the presence of sodium. Now, a piece of metallic sodium will be introduced into the lamp. The sodium will be vaporised by the heat, and will fill the lamp with its vapour. This vapour absorbs, quenches the light that it emits when luminous. There will thus be produced a black line exactly in the place of the bright yellow line.

It is evident that Kirchhoff, by this discovery, has furnished us with the means of interpreting the dark lines of the solar spectrum. For this purpose it is necessary to compare the bright lines in the spectra of the light of terrestrial substances, when *in the state of gas*, with the dark lines in the solar spectrum. When a group of bright lines coincides with a similar group of dark lines, then we know that the terrestrial substance producing the bright lines is present in the atmosphere of the sun. For it is this substance, and this substance alone, which, by its own peculiar power of absorption, can produce that particular group of dark lines. In this way Kirchhoff discovered the presence of several terrestrial elements in the solar atmosphere.

METHODS OF OBSERVATION

I now pass to the special methods of observation by which, in our investigations, we have applied these principles of spectrum analysis to the light of the heavenly bodies. I may here state that several circumstances unite to make

these observations very difficult and very irksome. In our climate, on few only, even of those nights in which the stars shine brilliantly to the naked eye, is the air sufficiently steady for these extremely delicate observations. Further, the light of the stars is feeble. This difficulty was met, in some measure, by the employment of a large telescope. The light of a star falling upon the surface of its object-glass of 8 inches aperture is gathered up and concentrated at the focus into a minute and brilliant point of light.

Another inconvenience arises from the apparent movement of the stars, caused by the rotation of the earth, which carries the astronomer and his instruments with it. This movement was counterbalanced by a movement given by clockwork to the telescope in the opposite direction. In practice, however, it is not easy to retain the image of a star for any length of time exactly within the jaws of a slit only the 1-300th of an inch apart. By patient perseverance these difficulties were overcome, and satisfactory results obtained. We considered that the trustworthiness of our observations must rest chiefly upon *direct and simultaneous comparison* of terrestrial spectra with those of celestial objects. For this purpose we contrived the apparatus which is represented in the diagram.

By this outer tube the instrument is adapted to the eye end of the telescope, and is carried round with it by the clock motion. Within this outer tube a second tube slides carrying a cylindrical lens. This lens is for the purpose of elongating the round point-like image of the star into a short line of light which is made to fall exactly within the jaws of a nearly-closed slit. Behind the slit, an achromatic lens, placed at the distance of its own focal length, causes the pencils to emerge parallel. They then pass into two prisms of dense flint glass. The spectrum which results from the decomposition of the light by the prisms is viewed through a small achromatic telescope. This telescope is provided with a micrometer screw, by which the positions of the lines of the spectra may be measured.

The light of the terrestrial substances which are to be compared with the stellar spectra is admitted into the instrument in the following manner:—

Over one-half of the slit is fixed a small prism, which receives the light reflected into it by the movable mirror placed above the tube. The mirror faces a clamp of ebonite, provided with forceps to contain fragments of the metals employed. These metals are rendered luminous in the state of gas by the intense heat of the sparks from a powerful induction coil. The light from the spark reflected into the instrument by means of the mirror and the little prism passes on to the prisms in company with that from the star. In the small telescope the two spectra are viewed in juxtaposition, so that the coincidence and relative positions of the bright lines in the spectrum of the spark with the dark lines in the spectrum of the star can be accurately determined.

MOON AND PLANETS

I now pass to the results of our observations.

I refer in a few words only to the moon and planets. These objects, unlike the stars and nebulæ, are not *original* sources of light. Since they shine by reflecting the sun's light, their spectra resemble the solar spectrum, and the only indications in their spectra which may become sources of knowledge to us are confined to any modifications which the solar light may have suffered, either in the atmospheres of the planets or by reflection at their surfaces.

Moon.—On the moon the results of our observations have been negative. The spectra of the various parts of the moon's surface, when examined under different conditions of illumination, showed no indication of an atmosphere about the moon. I also watched the spectrum of a star, as the dark edge of the moon advanced towards the star, and then occulted it. No signs of a lunar atmosphere presented themselves.

Jupiter.—In the spectrum of Jupiter, lines are seen which indicate the existence of an absorptive atmosphere about this planet. In this diagram these lines are presented as they appeared when viewed simultaneously with the spectrum of the sky, which at the time of observation reflected the light of the setting sun. One strong band corresponds with some terrestrial atmospheric lines, and probably indicates the presence of vapours similar to those which are about the earth. Another band has no counterpart amongst the lines of absorption of our atmosphere, and tells us of some gas or vapour which does not exist in the earth's atmosphere.

Saturn.—The spectrum of Saturn is feeble, but lines similar to those which distinguish the spectrum of Jupiter were detected. These lines are less strongly marked in the ansae of the rings, and show that the absorptive power of the atmosphere about the rings is less than that of the atmosphere which surrounds the ball. A distinguished foreigner present at the meeting, Janssen, has quite recently found that several of the atmospheric lines in this part of the spectrum are produced by aqueous vapour. It appears to be very probable that aqueous vapour exists in the atmospheres of Jupiter and Saturn.

Mars.—On one occasion some remarkable groups of lines were seen in the more refrangible part of the spectrum of Mars. These may be connected with the red colour which distinguishes this planet.*

Venus.—Though the spectrum of Venus is brilliant and the lines of Fraunhofer were well seen, no additional lines affording evidence of an atmosphere about Venus were detected. The absence of lines may be due to the circumstance that the light is probably reflected, not from the planetary surface,

* Later observations did not support this view.

but from clouds at some elevation above it. The light which reaches us in this way by reflection from clouds would not have been exposed to the absorbent action of the lower and denser strata of the planet's atmosphere.

THE FIXED STARS

The fixed stars, though immensely more remote, and less conspicuous in brightness than the moon and planets, yet, because they *are original sources of light*, furnish us with fuller indications of their nature.

To each succeeding age the stars have been a beauty and a mystery. Not only children, even the most thoughtful of men often repeat the sentiment expressed in the well-known lines—

“Twinkle, twinkle, pretty star,
How I wonder what you are.”

The telescope was appealed to in vain, for in the largest instruments the stars remain diskless, brilliant points merely.

The stars have indeed been represented as suns each upholding a dependent family of planets. This opinion rested *upon a possible analogy alone*. It was not more than a speculation. We possessed no certain knowledge *from observation* of the true nature of those remote points of light. This long and earnestly coveted information is at last furnished by spectrum analysis. We are now able to read in the light of each star some indications of its nature. Since I have not a magician's power to convert this theatre into an observatory, and so exhibit to you the spectra of the stars themselves, I have provided photographs of careful drawings. These photographs Mr. Ladd will exhibit upon the screen by means of the electric lamp. I will take first the spectra of two bright stars which we have examined with great care.

The upper one represents the spectrum of Aldebaran, and the other that of Betelgeux, the star marked Alpha in the Constellation of Orion.

The positions of all these dark lines, about eighty in each star, were determined by careful and repeated measures. These measured lines form but a small part of the numerous fine lines which may be seen in the spectra of these stars.

Beneath the spectrum of each star are represented the bright lines of the metals which have been compared with it. These terrestrial spectra appeared in the instrument as you now see them upon the screen, in *juxtaposition* with the spectrum of the star. By such an arrangement it is possible to determine with great accuracy whether or not any of these bright lines actually coincide with any of the dark lines. For example:

This closely double line is characteristic of sodium. You see that it

coincides, line for line, with a dark line similarly double in the star. The vapour of sodium is therefore present in the atmosphere of the star, and sodium forms one of the elements of the matter of this brilliant but remote star.

These three lines in the green are produced, so far as we know, by the luminous vapour of magnesium *alone*. These lines agree in position exactly, line for line, with three dark stellar lines. The conclusion therefore appears well founded that another of the constituents of this star is magnesium.

Again, there are two strong lines peculiar to the element *hydrogen*; one line has its place in the red part of the spectrum, the other at the blue limit of the green. Both of these correspond to dark lines of absorption in the spectrum of the star. Hydrogen therefore is present in the star.

In a similar way, other elements, among them bismuth, antimony, tellurium, mercury, have been shown to exist in the star.

Now, in reference to all these elements, the evidence does not rest upon the coincidence of *one* line, which would be worth but little, but upon the coincidence of a group of two, three, or more lines, occurring in different parts of the spectrum. Other corresponding lines are probably also present, but the faintness of the star's light limited our comparisons to the stronger lines of each element.

What elements do the numerous other lines in the star represent? Some of them are probably due to the vapours of other *terrestrial* elements which we have not yet compared with these stars. But may not some of these lines be the signs of primary forms of matter unknown upon the earth? Elements new to us may here show themselves, which form large and important series of compounds, and therefore give a special character to the physical conditions of these remote systems. In a similar manner the spectra of terrestrial substances have been compared with several other stars. The results are given in the diagrams. Five or six elements have been detected in Betelgeux. Ten other elements do not appear to have a place in the constitution of this star.

β <i>Pegasi</i>	.	.	.	contains sodium, magnesium, and perhaps barium.
<i>Sirius</i>	.	.	.	" sodium, magnesium, iron, and hydrogen.
<i>a Lyre (Vega)</i>	.	.	.	" sodium, magnesium, iron.
<i>Pollux</i>	.	.	.	" sodium, magnesium, iron.

About sixty other stars have been examined, all of which appear to have some elements in common with the sun and earth, but the selective grouping of the elements in each star is probably peculiar and unique.

A few stars, however, stand out from the rest, and appear to be characterised by a peculiarity of great significance. These stars are represented by Betelgeux and β *Pegasi*. The general grouping of the lines of absorption in these stars is peculiar, but the remarkable and exceptional feature of their

spectra is the absence of the two lines which indicate hydrogen, one line in the red and the other in the green.* These lines correspond to Fraunhofer's C and F. The absence of these lines in some stars shows that the lines C and F are not due to the aqueous vapour of the atmosphere.

We hardly venture to suggest that the planets, which may surround these suns, probably resemble them in not possessing the important element, hydrogen. To what forms of life could such planets be adapted? Worlds without water! A power of imagination like that possessed by Dante would be needed to people such planets with living creatures.

It is worthy of consideration that, with these few exceptions, the terrestrial elements which appear most widely diffused through the host of stars are precisely some of those which are essential to life such as it exists upon the earth—namely, hydrogen, sodium, magnesium, and iron. Besides, hydrogen, sodium, and magnesium represent the ocean, which is an essential part of a world constituted like the earth.

We learn from these observations that *in plan of structure* the stars, or at least the brightest of them, resemble the sun. Their light, like that of the sun, emanates from intensely white-hot matter, and passes through an atmosphere of absorbent vapours. With this unity of general plan of structure there exists a great diversity amongst the individual stars. Star differs from star in chemical constitution.†

When we had obtained this new information respecting the *true nature* of the stars, our attention was directed to the phenomena which specially distinguish some of the stars.

COLOURS OF THE STARS

When the air is clear, especially in Southern climes, the twinkling stars do not all resemble diamonds: here and there may be seen in beauteous contrast *richly coloured gems*.

The colour of the light of the stars which are bright to the naked eye is always some tint of *red*, *orange*, or *yellow*. When, however, a telescope is employed, in close companionship with many of these ruddy and orange stars other fainter stars become visible, the colour of which may be *blue*, or *green*, or *purple*.

Now it appeared to us to be probable that the origin of these differences of colour among the stars may be indicated by their spectra.

Since we had found that the source of the light of the stars is incandescent solid or liquid matter, it appeared to be very probable that at the time of its emission the light of all the stars is *white* alike. The colours observed

* Afterwards seen. See p. 78.

† More correctly on the evolutional conditions of their atmospheres.

amongst them must, then, be caused by some modification suffered by the light after its emission.

Again, it was obvious that if the dark lines of absorption were more numerous, or stronger, in some parts of the spectrum, then those colours would be subdued in power, relatively to the colours in which few lines only occur. These latter colours remaining strong would predominate, and give to the light, originally white, their own tints.

These suppositions have been confirmed by observation.

Mr. Ladd will throw upon the screen the spectrum of *Sirius*, which may be taken as an illustration of the *stars the light of which is white*.

As might be expected, the spectra of these stars are remarkable for their freedom from strong groups of absorption-lines. The dark lines, though present in great number, are all, with one exception, very thin and faint, and too feeble to modify the original whiteness of the light. The *one* exception consists of three very strong single lines; one line corresponding to Fraunhofer's C, one to F, and the other near G. Two of these certainly indicate the presence of hydrogen. This peculiarity, which seems invariably connected with colourless stars, is very suggestive, and invites speculation. May it be a sign of a temperature of extreme fierceness?

Let us now examine the spectrum of an *orange star*.

This diagram represents the spectrum of the brighter of the two stars which form the double star α *Herculis*. In the spectrum of this star the green and blue parts of the light, and also the deep red, are subdued with strong groups of lines, while the orange and yellow rays preserve nearly their original intensity, and therefore predominate in the star's light.

The question yet remained to be answered: Would the faint telescopic stars, which are *blue*, *green*, and *purple*, and which are never found alone in the heavens, but always under the protection of a strong *ruddy* or *orange* star, furnish spectra in accordance with this theory?

With some little difficulty, and by means of a special arrangement of the spectrum apparatus, we succeeded in observing the spectra of the components of some double stars. There will now be thrown upon the screen the well-known double star β *Cygni*. In a large telescope the colours of the two stars are beautifully contrasted, as they now appear upon the screen. The spectra of these stars are now shown. The upper spectrum represents the orange star, the lower one that of its beautiful but feeble companion. In the orange star, you observe that the dark lines are strongest and most closely grouped in the blue and violet parts of the spectrum; and the orange rays, therefore, which are comparatively free from lines, predominate.

In the delicate blue companion, the strongest groups of lines are found in the yellow, orange, and in part of the red. In the arrangement of these

groups of lines we have a sufficient cause for the predominance of the other portions of the spectrum which unite in the eye to give the blue purple colour of the light of this star.

We have, therefore, shown that the colours of the stars are produced by the vapours existing in their atmospheres. The chemical constitution of a star's atmosphere will depend upon the elements existing in the star and upon its temperature.

VARIABLE STARS

The brightness of many of the stars is found to be variable. From night to night, from month to month, or from season to season, their light may be observed to be continually changing, at one time increasing, at another time diminishing. The careful study of these variable stars, by numerous observers, has shown that their continual changes do not take place in an uncertain or irregular manner. The greater part of these remarkable objects wax and wane in accordance with a fixed law of periodic variation which is peculiar to each.

We have been seeking for some time to throw light upon this strange phenomenon by means of the observation of their spectra. If in any case the periodic variation of brightness is associated with *physical changes* occurring in the star, we might obtain some information by means of the prism. Again, if the diminution in brightness of a star should be caused by the interposition of a dark body, then, in that case, if the dark body be surrounded with an atmosphere, its presence might possibly be revealed to us, by the appearance of additional lines of absorption in the spectrum of the star when at its minimum. One such change in the spectrum of a variable star we believe we have already observed.

Betelgeux is a star of a moderate degree of variability. When this star was at its maximum brilliancy in February last we missed a group of lines, the exact position of which we had determined with great accuracy by micrometric measurements some two years before.

We have observed the spectra of several variable stars at different phases of their periodic variation, but our results are not yet complete.

It is worthy of notice that the variable stars which have a ruddy or an orange tint possess spectra analogous to that of Betelgeux and β Pegasi.

As an example of this group of variable stars, Mr. Ladd will throw upon the screen the spectrum of μ Cephei when at its maximum.

TEMPORARY STARS

With the variable stars modern opinion would associate the remarkable phenomena of the so-called *new stars* which occasionally, but at long intervals,

have suddenly appeared in the sky. In no case has a permanently bright star been added to the heavens. The splendour of all these objects was temporary only, though whether they died out or still exist as extremely faint stars is uncertain. In the case of the two modern temporary stars—that seen by Mr. Hind in 1845, and the bright star recently observed in Corona—though they have lost their ephemeral glory, they still continue as stars of the 10th and 11th magnitude.

The old theories respecting these strange objects must be rejected. We cannot believe with Tycho Brahe that objects so ephemeral are *new creations*, nor with Riccioli that they are stars brilliant on one side only which have been suddenly turned round by the Deity. The theory that they have suddenly darted towards us with a velocity greater than that of light, from a region of remote invisibility, will not now find supporters.

On May 12 last a star of the second magnitude suddenly burst forth in the constellation of the Northern Crown. Thanks to the kindness of the discoverer of this phenomenon, Mr. Birmingham, of Tuam, I was enabled conjointly with Dr. Miller to examine the spectrum of this star on May 16, when it had not fallen much below the third magnitude.

Perhaps I ought to state that Mr. Barker, of London, Canada W., who announced in the *Canadian Free Press* that he observed a star in Corona on May 14, and that it was of the third magnitude, now claims, in a letter addressed to Mr. Hind, to have seen the star on May 4, from which time he states that it increased in brilliancy until the 10th, and after that day diminished in brightness.

The spectrum of this star consists of two distinct spectra. One of these is formed by these four bright lines. The other spectrum is analogous to the spectra of the sun and stars.

There, two spectra represent two distinct sources of light. Each spectrum is formed by the decomposition of light, which is independent of the light which gives birth to the other spectrum.

The continuous spectrum crowded with groups of dark lines shows that there exists a photosphere of incandescent solid or liquid matter. Further, that there is an atmosphere of cooler vapours which give rise by absorption to the group of dark lines.

So far, the constitution of this object is analogous to that of the sun and stars, but in addition there is the second spectrum, which consists of bright lines. There is therefore a second and distinct source of light, and this must be, as the character of the spectrum shows, *luminous gas*. Now the two principal of the bright lines, by their position in the spectrum, informs us that one of the luminous gases is *hydrogen*. The great brightness of these lines shows that the luminous gas is probably hotter than the photosphere. These

facts, taken in connection with the comparative suddenness of the outburst of light in the star, and its immediate very rapid decline in brightness, *from the second magnitude down to the eighth magnitude in twelve days*, suggested to us the startling speculation that *the star became suddenly enwrapt in the flames of burning hydrogen*. In consequence, it may be, of some great convulsion, enormous quantities of gas were set free. A large part of this gas consisted of hydrogen, which was burning about the star in combination with some other element. This flaming gas emitted the light represented by the spectrum of bright lines. The greatly increased brightness of the spectrum of the other part of the star's light may show that this fierce gaseous conflagration had heated to a more vivid incandescence the solid matter of the photosphere. As the free hydrogen became exhausted the flames gradually abated, the photosphere became less vivid, and the star waned down to its former brightness.

We must not forget that light, though a swift messenger, requires time to pass from the star to us. The great physical convulsion which is new to observers on the earth is already an event of the past with respect to the star itself. For years the star has existed under the new conditions which followed this fiery catastrophe.

NEBULÆ

I pass now to objects of another order.

When the eye is aided by a telescope of even moderate power, a large number of faintly luminous patches and spots come forth from the darkness of the sky, which are in strong contrast with the brilliant, but pointlike images of the stars. A few of these objects may be easily discerned to consist of very faint stars closely aggregated together. Many of these strange objects remain, even in the largest telescopes, unresolved into stars, and resemble feebly shining clouds, or masses of phosphorescent haze. During the last 150 years the intensely important question has been continually before the minds of astronomers, "What is the true nature of these faint comet-like masses?"

The interest connected with an answer to this question has much increased since Sir William Herschel suggested that these objects are portions of the primordial material out of which the existing stars have been fashioned, and further that in these objects we may study some of the stages through which the suns and planets pass in their development from luminous cloud.

The telescope has failed to give any certain information of the nature of the nebulae. It is true that each successive increase of aperture has resolved more of these objects into bright points, but at the same time other fainter nebulae have been brought into view, and fantastic wisps and diffused patches

of light have been seen, which the mind almost refuses to believe can be due to the united glare of innumerable suns still more remote.

Spectrum analysis, if it could be successfully applied to objects so excessively faint, was obviously a method of investigation specially suitable for determining whether any essential physical distinction separates the nebulae from the stars.

I selected for the first attempt, in August 1864, one of the class of small but comparatively bright nebulae.

My surprise was very great, on looking into the small telescope of the spectrum apparatus, to perceive that there was no appearance of a band of coloured light, such as a star would give, but in place of this there were three isolated *bright lines* only.

This observation was sufficient to solve the long agitated inquiry in reference to this object at least, and to show that it was not a *group of stars*, but a *true nebula*.

A spectrum of this character, so far as our knowledge at present extends, can be produced only by light which has emanated from matter in the *state of gas*. The light of this nebula, therefore, was not emitted from incandescent solid or liquid matter, as is the light of the sun and stars, but from *glowing or luminous gas*.

It was of importance to learn, if possible, from the *position* of these bright lines, the chemical nature of the gas or gases of which this nebula consists.

Measures taken by the micrometer of the most brilliant of the bright lines showed that this line occurs in the spectrum very nearly in the position of the brightest of the lines in the spectrum of nitrogen. The experiment was then made of comparing the spectrum of nitrogen directly with the bright lines of the nebula. I found that the brightest of the lines of the nebula *coincided* with the strongest of the lines which are peculiar to nitrogen.* It may be, therefore, that the occurrence of this one line only, indicates a form of matter more elementary than nitrogen, and which our analysis has not yet enabled us to detect.

In a similar manner the faintest of the lines was found to coincide with the green line of hydrogen.

The middle line of the three lines which form the spectrum of the nebula does not coincide with a very strong line in the spectra of about thirty of the terrestrial elements. It is not far from the line of barium, but it does not coincide with it. Besides these bright lines there was also an exceedingly faint continuous spectrum. This spectrum had no apparent breadth, and must therefore have been formed by a minute point of light. Its position, crossing the bright line about the middle, showed that the point of light was situated

* This apparent coincidence was not maintained when a more powerful spectroscope was used. See pp. 185 and 186.

about the centre of the nebula. Now this nebula possesses a minute but bright 'nucleus.' We learn from this observation that the matter of the nucleus is almost certainly not in a state of gas, as is the material of the surrounding nebula. It consists of opaque matter, which may exist in the form of an incandescent fog of solid or liquid particles.

The new and unexpected results arrived at by the prismatic examination of this nebula showed the importance of examining as many as possible of these remarkable bodies. Would all the nebulæ give similar spectra? Especially it was of importance to ascertain whether those nebulæ which the telescope had certainly resolved into a close aggregation of bright points would give a spectrum indicating gaseity.

The observation with the prism of these objects is extremely difficult on account of their great faintness. Besides this, it is only when the sky is very clear and the moon is absent that the prismatic arrangement of their light is even possible. During the last two years I have examined the spectra of more than sixty nebulæ and clusters. These may be divided into two great groups. One group consists of the nebulæ which give a spectrum similar to the one I have already described, or else of one or two only of the three bright lines. Of the sixty objects examined about one-third belong to the class of gaseous bodies. The light from the remaining forty nebulæ and clusters becomes spread out by the prism into a spectrum which is *apparently* continuous.

I will exhibit upon the screen a few of the more remarkable of the nebulæ *which are gaseous in their constitution.*

This photograph is from a drawing by Lord Rosse of a small nebula in Aquarius (I. H. IV.)

We have here a gaseous system which reminds the observer of Saturn and his rings. The ring is seen edgeways. The three bright lines represent the spectrum into which the light of this object is resolved by the prism.

In this other nebula we find probably an analogous general form of structure. In consequence of the nebula lying in a different position to us, its ring is seen not edgeways but open on the flat. The spectrum consists of three bright lines.

The arrangement of the streams of light in the object now on the screen, 18 H. IV., suggests a spiral structure. This nebula is remarkable as the only one in which, in addition to the three bright lines, a fourth line was also seen.

The most remarkable, and possibly the nearest to our system, of the nebulæ presenting a *ring formation*, is the well-known Annular Nebula in Lyra. The spectrum consists of one bright line only.* When the slit of

* More powerful instruments show the other lines.

the instrument crosses the nebula, the line consists of two brighter portions corresponding to the sections of the ring. A much fainter line joins them, which shows that the faint central portion of the nebula has a similar constitution.

A nebula remarkable for its large extent and peculiar form is that known as the *Dumb-bell Nebula*. The spectrum of this nebula consists of one line only. A prismatic examination of the light from different parts of this object showed that it is throughout of a similar constitution.

The most widely known, perhaps, of all the nebulæ is that remarkable cloud-like object in the sword-handle of Orion.

This object is also gaseous. Its spectrum consists of three bright lines. Lord Rosse informs me that the bluish green matter of the nebula has not been resolved by his telescope. In some parts, however, he sees a large number of very minute *red* stars, which, though apparently connected with the irresolvable matter of the nebula, are yet doubtless distinct from it. These stars would be too faint to furnish a visible spectrum.

I now pass to some examples of the other great group of Nebulæ and Clusters.

All the true *Clusters*, which are resolved by the telescope into distinct bright points, give a spectrum, which does not consist of separate bright lines, but is *apparently* continuous in its light. There are many *nebulæ* which furnish a similar spectrum.

I take, as an example of these nebulæ, the Great Nebula in Andromeda, which is visible to the naked eye, and is not seldom mistaken for a comet. The spectrum of this nebula, though apparently continuous, has some suggestive peculiarities. The whole of the red and part of the orange are wanting.* Besides this character, the brighter parts of the spectrum have a very unequal and mottled appearance.

It is remarkable that the easily resolved cluster in Hercules has a spectrum precisely similar. The prismatic connection of this cluster with the nebula in Andromeda is confirmed by telescopic observation. Lord Rosse has discovered in this cluster dark streaks or lines similar to those which are seen in the nebula in Andromeda.

In connection with these observations it was of great interest to ascertain whether this broad classification afforded by the prism of the nebulæ and clusters would correspond with the indications of resolvability furnished by the telescope. Would it be found that all the *unresolved* nebulæ are *gaseous*, and that those which give a *continuous spectrum* are *clusters of stars*?

Lord Oxmantown has examined all the observations of the sixty nebulæ and clusters in my list, which have been made with the great reflecting telescope

* Under more favourable conditions these parts of the spectrum were seen by me later.

erected by his father, the Earl of Rosse. The results are given in this diagram :

	Continuous Spectrum.	Gaseous Spectrum.
Clusters 10	0
Resolved, or Resolved? . 5	0
Resolvable, or Resolvable? 10	6
Blue or Green, no resolva-} 0	4
bility, no resolvability seen} 6	<u>31</u>	<u>5</u>
Not observed by Lord Rosse 10	<u>41</u>	<u>19</u>

Considering the great difficulty of successful telescopic observation of these objects, the correspondence between the results of prismatic and telescopic observation may be regarded as close and suggestive.

Half of the nebulae which give a continuous spectrum have been resolved, and about one-third more are probably resolvable; while of the gaseous nebulae *none have been certainly resolved*, according to Lord Rosse.

The inquiry now presses itself upon us—What superstructure of interpretation have we a right to raise upon the new facts with which the prism has furnished us?

Is the existence of the gaseous nebulae an evidence of the reality of that primordial nebulous matter required by the theories of Sir William Herschel and Laplace?

Again, if we do not accept the view that these nebulae are composed of portions of the original elementary matter out of which suns and planets have been elaborated, what is the cosmical rank and relation which we ought to assign to them? As aids to a *future* determination of these great questions I will refer in a few words to some other observations.

COMETS

There are objects in the heavens which occasionally, and under some conditions, resemble closely some of the nebulae. In some positions in their orbits some of the comets appear as round vaporous masses, and, except by their motion, cannot be distinguished from nebulae. Does this occasional general resemblance indicate a similarity of nature? If such be the case—if the material of the comets is similar to that of the nebulae—then the study of the wonderful changes which comets undergo in the neighbourhood of the sun may furnish useful information for a more correct interpretation of the structure and condition of the nebulae. In 1864 Donati found that the spectrum of a comet visible in that year consisted of *bright lines*.

Last January a small telescopic comet was visible. Its appearance in a

large telescope is represented on the screen. It was a nearly circular, very faint vaporous mass. Nearly in the centre, a small and rather dim nucleus was seen. When this object was viewed in the spectroscope, two spectra were distinguished. A very faint continuous spectrum of the coma, showing that it was visible by reflecting solar light. About the middle of this faint spectrum a bright point was seen. This bright point is the spectrum of the nucleus, and shows that its light is different from that of the coma. This short bright line indicates that the nucleus of this comet was self-luminous, and further, the position of this line of the spectrum suggests that *the material of the comet was similar to the matter of which the gaseous nebulae consist.**

MEASURES OF THE INTRINSIC BRIGHTNESS OF THE NEBULÆ

It appeared to me that some information as to the nature of the nebulae might be obtained from observations of another order. If physical changes of the magnitude necessary for the conversion of these gaseous bodies into suns are now in progress in the nebulae, surely this process of development would be accompanied by marked changes in the intrinsic brightness of their light, and in their size.

Now since the spectroscope shows these bodies to be continuous masses of gas, it is possible to obtain an approximate measure of their *real brightness*. It is known that, as long as a distant object remains of sensible size, its brightness remains unaltered. By a new photometric method I found the *intrinsic* intensity of the light of three of the gaseous nebulae in terms of a sperm candle burning at the rate of 158 grains per hour:

Nebula No. 4628,	$\frac{1}{1508}$ th part of the intensity of the candle.
Annular Nebula, Lyra, $\frac{1}{8032}$ nd	" " "
Dumb-bell Nebula,	$\frac{1}{19604}$ th " " "

These numbers represent not the *apparent* brightness only, but the *true brightness* of these luminous masses, except so far as it may have been diminished by a possible power of extinction existing in cosmical space, and by the absorption of our atmosphere. It is obvious that similar observations made at considerable intervals of time may show whether the light of these objects is undergoing increase or diminution, or is subject to a periodic variation. If the Dumb-bell Nebula, the feeble light of which is not more than the one twenty-thousandth part of that of a candle, be in accordance with popular theory a *sun-germ*, then it is scarcely possible to put in an intelligible form the enormous number of times by which its light must increase before this faint nebula, feebler now in its glimmering than a rushlight, can rival the dazzling splendour of our sun.

* This apparent similarity was not supported by later observations. See p. 277.

MEASURES OF THE NEBULÆ

Some of the nebulae are sufficiently defined in outline to admit of accurate measurement. By means of a series of micrometric observations it will be possible to ascertain whether any considerable alteration in size takes place in the nebulae.

Mr. Alexander Herschel has recently succeeded in subjecting another order of the heavenly bodies to prismatic analysis. He has obtained the spectrum of a bright meteor and also the spectra of some of the trains which meteors leave behind them. A remarkable result of his observations appears to be that sodium in the state of luminous vapour is present in the trains of most meteors.

CONCLUSION

In conclusion, the new knowledge that has been gained from these observations with the prism may be summed up as follows :

1. All the brighter stars, at least, have a structure analogous to that of the sun.
2. The stars contain material elements common to the sun and earth.
3. The colours of the stars have their origin in the chemical constitution of the atmospheres which surround them.
4. The changes in brightness of some of the variable stars are attended with changes in the lines of absorption of their spectra.
5. The phenomena of the star in Corona appear to show that in this object at least great physical changes are in operation.
6. There exist in the heavens *true nebulae*. These objects consist of luminous gas.
7. The material of comets is very similar to the matter of the gaseous nebulae, and may be identical with it.*
8. The bright points of the star-clusters may not be in all cases stars of the same order as the separate bright stars.

It may be asked what cosmical theory of the origin and relations of the heavenly bodies do these new facts suggest? It would be easy to speculate, but it appears to me that it would not be philosophical to dogmatise at present on a subject of which we know so very little. Our views of the universe are undergoing important changes; let us wait for more facts, with minds unfettered by any dogmatic theory, and therefore free to receive the obvious teaching, whatever it may be, of new observations.

* Later observations showed this view to be incorrect.

PRESIDENTIAL ADDRESS, BRITISH ASSOCIATION FOR THE
ADVANCEMENT OF SCIENCE, CARDIFF, 1891 *

(*Report Brit. Assoc.*, 1891, p. 1)

IT is now many years since this Association has done honour to the science of Astronomy in the selection of its President.

Since Sir George Airy occupied the chair in 1851, and the late Lord Wrottesley nine years later, in 1860, other sciences have been represented by the distinguished men who have presided over your meetings.

The very remarkable discoveries in our knowledge of the heavens which have taken place during this period of thirty years—one of amazing and ever-increasing activity in all branches of science—have not passed unnoticed in the addresses of your successive Presidents; still it seems to me fitting that I should speak to you to-night chiefly of those newer methods of astronomical research which have led to those discoveries, and which have become possible by the introduction since 1860 into the observatory of the spectroscope and the modern photographic plate.

In 1866 I had the honour of bringing before this Association, at one of the evening lectures, an account of the firstfruits of the novel and unexpected advances in our knowledge of the celestial bodies which followed rapidly upon Kirchhoff's original work on the solar spectrum and the interpretation of its lines.

Since that time a great harvest has been gathered in the same field by many reapers. Spectroscopic astronomy has become a distinct and acknowledged branch of the science, possessing a large literature of its own and observatories specially devoted to it. The more recent discovery of the gelatine dry plate has given a further great impetus to this modern side of astronomy, and has opened a pathway into the unknown of which even an enthusiast thirty years ago would scarcely have dared to dream.

In no science, perhaps, does the sober statement of the results which have been achieved appeal so strongly to the imagination, and make so evident the almost boundless powers of the mind of man. By means of its light alone, to analyse the chemical nature of a far distant body; to be able to reason about its present state in relation to the past and future; to measure within an English mile or less per second the otherwise invisible motion which it may

* On some of the problems considered in this Address our knowledge has been notably enlarged by subsequent observations. After some consideration, I have decided not to attempt to bring the Address up to date on these points by the addition of footnotes, but to let it remain as representing the advanced position of the science of Astrophysics near the close of the last century.

Some of the points on which advance has been made, as the experimental establishment of the pressure of radiation, have been already noticed in the footnotes added to my papers. (1909.)

have towards or from us; to do more—to make even that which is darkness to our eyes light, and from vibrations which our organs of sight are powerless to perceive to evolve a revelation in which we see mirrored some of the stages through which the stars may pass in their slow evolutional progress—surely the record of such achievements, however poor the form of words in which they may be described, is worthy to be regarded as the scientific epic of the present century.

I do not purpose to attempt a survey of the progress of spectroscopic astronomy from its birth at Heidelberg in 1859, but to point out what we do know at present, as distinguished from what we do not know, of a few only of its more important problems, giving a prominent place, in accordance with the traditions of this chair, to the work of the last year or two.

In the spectroscope itself advances have been made by Lord Rayleigh by his discussion of the theory of the instrument, and by Professor Rowland in the construction of concave gratings.

Lord Rayleigh has shown that there is not the necessary connection, sometimes supposed, between dispersion and resolving power, as besides the prism or grating other details of construction and of adjustment of a spectroscope must be taken into account.

The resolving power of the prismatic spectroscope is proportional to the length of path in the dispersive medium. For the heavy flint glass used in Lord Rayleigh's experiments the thickness necessary to resolve the sodium lines came out 1·02 cm. If this be taken as a unit, the resolving power of a prism of similar glass will be in the neighbourhood of the sodium lines equal to the number of centimetres of its thickness. In other parts of the spectrum the resolving power will vary inversely as the third power of the wave-length, so that it will be eight times as great in the violet as in the red. The resolving power of a spectroscope is therefore proportional to the total thickness of the dispersive material in use, irrespective of the number, the angles, or the setting of the separate prisms into which, for the sake of convenience, it may be distributed.

The resolving power of a grating depends upon the total number of lines on its surface, and the order of spectrum in use; about a thousand lines being necessary to resolve the sodium lines in the first spectrum.

As it is often of importance in the record of observations to state the efficiency of the spectroscope with which they were made, Professor Schuster has proposed the use of a unit of purity as well as of resolving power; for the full resolving power of a spectroscope is realised in practice only when a sufficiently narrow slit is used. The unit of purity also is to stand for the separation of two lines differing by one-thousandth of their own wave-length—about the separation of the sodium pair at D.

A further limitation may come in from the physiological fact that, as Lord Rayleigh has pointed out, the eye when its full aperture is used is not a perfect instrument. If we wish to realise the full resolving power of a spectroscope, therefore, the emergent beam must not be larger than about one-third of the opening of the pupil.

Up to the present time the standard of reference for nearly all spectroscopic work continues to be Ångström's map of the solar spectrum, and his scale based upon his original determinations of absolute wave-length. It is well known, as was pointed out by Thalén in his work on the spectrum of iron in 1884, that Ångström's figures are slightly too small, in consequence of an error existing in a standard metre used by him. The corrections for this have been introduced into the tables of the wave-lengths of terrestrial spectra collected and revised by a Committee of this Association from 1885 to 1887. Last year the Committee added a table of corrections to Rowland's scale.

The inconvenience caused by a change of standard scale is, for a time at least, considerable; but there is little doubt that in the near future Rowland's photographic map of the solar spectrum, and his scale based on the determinations of absolute wave-length by Pierce and Bell, or the Potsdam scale based on original determinations by Müller and Kempf, which differs very slightly from it, will come to be exclusively adopted.

The great accuracy of Rowland's photographic map is due chiefly to the introduction by him of concave gratings, and of a method for their use, by which the problem of the determination of relative wave-lengths is simplified to measures of near coincidences of the lines in different spectra by a micrometer.

The concave grating and its peculiar mounting, in which no lenses or telescope are needed, and in which all the spectra are in focus together, formed a new departure of great importance in the measurement of spectral lines. The valuable method of photographic sensitisers for different parts of the spectrum has enabled Professor Rowland to include in his map the whole visible solar spectrum, as well as the ultra-violet portion as far as it can get through our atmosphere. Some recent photographs of the solar spectrum, which include A, by Mr. George Higgs, are of great technical beauty.

During the past year the results of three independent researches have appeared, in which the special object of the observers has been to distinguish the lines which are due to our atmosphere from those which are truly solar—the maps of M. Thollon, which, owing to his lamented death just before their final completion, have assumed the character of a memorial of him; maps by Dr. Becker; and sets of photographs of a high and a low sun by Mr. McClean.

At the meeting of this Association in Bath, M. Janssen gave an account

of his own researches on the terrestrial lines of the solar spectrum, which owe their origin to the oxygen of our atmosphere. He discovered the remarkable fact that while the intensity of one class of bands varies as the density of the gas, other diffuse bands vary as the square of the density. These observations are in accordance with the work of Egoroff and of Olszewski, and of Liveing and Dewar on condensed oxygen. In some recent experiments Olszewski, with a layer of liquid oxygen thirty millimetres thick, saw, as well as four other bands, the band coincident with Fraunhofer's A : a remarkable instance of the persistence of absorption through a great range of temperature. The light which passed through the liquid oxygen had a light blue colour resembling that of the sky.

Of not less interest are the experiments of Knut Ångström, which show that the carbonic acid and aqueous vapour of the atmosphere reveal their presence by dark bands in the invisible infra-red region, at the positions of bands of emission of these substances.

It is now some thirty years since the spectroscope gave us for the first time certain knowledge of the nature of the heavenly bodies, and revealed the fundamental fact that terrestrial matter is not peculiar to the solar system, but is common to all the stars which are visible to us.

In the case of a star such as Capella, which has a spectrum almost identical with that of the sun, we feel justified in concluding that the matter of which it is built up is similar, and that its temperature is also high, and not very different from the solar temperature. The task of analysing the stars and nebulæ becomes, however, one of very great difficulty when we have to do with spectra differing from the solar type. We are thrown back upon the laboratory for the information necessary to enable us to interpret the indications of the spectroscope as to the chemical nature, the density and pressure, and the temperature of the celestial masses.

What the spectroscope immediately reveals to us are the waves which were set up in the ether filling all interstellar space, years or hundreds of years ago, by the motions of the molecules of the celestial substances. As a rule it is only when a body is gaseous and sufficiently hot that the motions within its molecules can produce bright lines and a corresponding absorption. The spectra of the heavenly bodies are indeed to a great extent absorption spectra, but we have usually to study them through the corresponding emission spectra of bodies brought into the gaseous form and rendered luminous by means of flames or of electric discharges. In both cases, unfortunately, as has been shown recently by Professors Liveing and Dewar, Wüllner, E. Wiedemann, and others, there appears to be no certain direct relation between the luminous radiation as shown in the spectroscope and the temperature of the flame, or of

the gaseous contents of the vacuum tube, that is, in the usual sense of the term as applied to the mean motion of all the molecules. In both cases, the vibratory motions within the molecules to which their luminosity is due are almost always much greater than would be produced by encounters of molecules having motions of translation no greater than the average motions which characterise the temperature of the gases as a whole. The temperature of a vacuum tube through which an electric discharge is taking place may be low, as shown thermometrically, quite apart from the consideration of the extreme smallness of the mass of gas, but the vibrations of the luminous molecules must be violent in whatever way we suppose them to be set up by the discharge: if we take Schuster's view that comparatively few molecules are carrying the discharge, and that it is to the fierce encounters of these alone that the luminosity is due, then, if all the molecules had similar motions, the temperature of the gas would be very high.

So in flames where chemical changes are in progress, the vibratory motions of the molecules which are luminous may be, in connection with the energy set free in these changes, very different from those corresponding to the mean temperature of the flame.

Under the ordinary conditions of terrestrial experiments, therefore, the temperature or the mean *vis viva* of the molecules may have no direct relation to the total radiation, which, on the other hand, is the sum of the radiation due to each luminous molecule.

These phenomena have recently been discussed by Ebert from the standpoint of the electro-magnetic theory of light.

Very great caution is therefore called for when we attempt to reason by the aid of laboratory experiments to the temperature of the heavenly bodies from their radiation, especially on the reasonable assumption that in them the luminosity is not ordinarily associated with chemical changes or with electrical discharges, but is due to a simple glowing from the ultimate conversion into molecular motion of the gravitational energy of shrinkage.

In a recent paper Stas maintains that electric spectra are to be regarded as distinct from flame spectra, and from researches of his own that the pairs of lines of the sodium spectrum other than D are produced only by disruptive electric discharges. As these pairs of lines are found reversed in the solar spectrum, he concludes that the sun's radiation is due mainly to electric discharges. But Wolf and Diacon, and later, Watts, observed the other pairs of lines of the sodium spectrum when the vapour was raised above the ordinary temperature of the Bunsen flame. Recently, Liveing and Dewar saw easily, besides D, the citron and green pairs, and sometimes the blue pair and the orange pair, when hydrogen charged with sodium vapour was burning at different pressures in oxygen. In the case of sodium vapour, therefore, and presumably

in all other vapours and gases, it is a matter of indifference whether the necessary vibratory motion of the molecules is produced by electric discharges or by flames. The presence of lines in the solar spectrum which we can only produce electrically is an indication, however, as Stas points out, of the high temperature of the sun.

We must not forget that the light from the heavenly bodies may consist of the combined radiations of different layers of gas at different temperatures, and possibly be further complicated to an unknown extent by the absorption of cooler portions of gas outside.

Not less caution is needed if we endeavour to argue from the broadening of lines and the coming in of a continuous spectrum as to the relative pressure of the gas in the celestial atmospheres. On the one hand, it cannot be gainsaid that in the laboratory the widening of the lines in a Plücker's tube follows upon increasing the density of the residue of hydrogen in the tube, when the vibrations are more frequently disturbed by fresh encounters; and that a broadening of the sodium lines in a flame at ordinary pressure is produced by an increase of the quantity of sodium in the flame; but it is doubtful if pressure, as distinguished from quantity, does produce an increase of the breadth of the lines. An individual molecule of sodium will be sensibly in the same condition, considering the relatively enormous number of the molecules of the other gases, whether the flame is scantily or copiously fed with the sodium salt. With a small quantity of sodium vapour the intensity will be feeble except near the maximum of the lines; when, however, the quantity is increased the comparative transparency on the sides of the maximum will allow the light from the additional molecules met with in the path of the visual ray to strengthen the radiation of the molecules farther back, and so increase the breadth of the lines.

In a gaseous mixture it is found, as a rule, that at the same pressure or temperature as the encounters with similar molecules become fewer, the spectral lines will be affected as if the body were observed under conditions of reduced quantity or temperature.

In their recent investigation of the spectroscopic behaviour of flames under various pressures up to forty atmospheres, Professors Liveing and Dewar have come to the conclusion that, though the prominent feature of the light emitted by flames at high pressure appears to be a strong continuous spectrum, there is not the slightest indication that this continuous spectrum is produced by the broadening of the lines of the same gases at low pressure. On the contrary, photometric observations of the brightness of the continuous spectrum, as the pressure is varied, show that it is mainly produced by the mutual action of the molecules of a gas. Experiments on the sodium spectrum were carried up to a pressure of forty atmospheres without producing any definite effect on the

width of the lines which could be ascribed to the pressure. In a similar way the lines of the spectrum of water showed no signs of expansion up to twelve atmospheres; though more intense than at ordinary pressure, they remained narrow and clearly defined.

It follows, therefore, that a continuous spectrum cannot be considered, when taken alone, as a sure indication of matter in the liquid or the solid state. Not only, as in the experiments already mentioned, such a spectrum may be due to gas when under pressure, but, as Maxwell pointed out, if the thickness of a medium, such as sodium vapour, which radiates and absorbs different kinds of light, be very great, and the temperature high, the light emitted will be of exactly the same composition as that emitted by lamp-black at the same temperature, for the radiations which are feebly emitted will be also feebly absorbed, and can reach the surface from immense depths. Schuster has shown that oxygen, even in a partially exhausted tube, can give a continuous spectrum when excited by a feeble electric discharge.

Compound bodies are usually distinguished by a banded spectrum; but on the other hand such a spectrum does not necessarily show the presence of compounds, that is, of molecules containing different kinds of atoms, but simply of a more complex molecule, which may be made up of similar atoms, and be therefore an allotropic condition of the same body. In some cases, for example, in the diffuse bands of the absorption spectrum of oxygen, the bands may have an intensity proportional to the square of the density of the gas, and may be due either to the formation of more complex molecules of the gas with increase of pressure, or it may be to the constraint to which the molecules are subject during their encounters with one another.

It may be thought that at least in the coincidences of bright lines we are on the solid ground of certainty, since the length of the waves set up in the ether by a molecule, say of hydrogen, is the most fixed and absolutely permanent quantity in nature, and is so of physical necessity, for with any alteration the molecule would cease to be hydrogen.

Such would be the case if the coincidence were certain; but an absolute coincidence can be only a matter of greater or less probability, depending on the resolving power employed, on the number of the lines which correspond, and on their characters. When the coincidences are very numerous, as in the case of iron and the solar spectrum, or the lines are characteristically grouped, as in the case of hydrogen and the solar spectrum, we may regard the coincidence as certain; but the progress of science has been greatly retarded by resting important conclusions upon the apparent coincidence of single lines, in spectrometers of very small resolving power. In such cases, unless other reasons supporting the coincidence are present, the probability of a real coincidence is almost too small to be of any importance, especially in

the case of a heavenly body which may have a motion of approach or of recession of unknown amount.

But even here we are met by the confusion introduced by multiple spectra, corresponding to different molecular groupings of the same substance; and, further, to the influence of substances in vapour upon each other; for when several gases are present together, the phenomena of radiation and reversal by absorption are by no means the same as if the gases were free from each other's influence, and especially is this the case when they are illuminated by an electric discharge.

I have said as much as time will permit, and I think indeed sufficient, to show that it is only by the laborious and slow process of most cautious observation that the foundations of the science of celestial physics can be surely laid. We are at present in a time of transition, when the earlier, and, in the nature of things, less precise observations are giving place to work of an order of accuracy much greater than was formerly considered attainable with objects of such small brightness as the stars.

The accuracy of the earlier determinations of the spectra of the terrestrial elements is in most cases insufficient for modern work on the stars as well as on the sun. They fall much below the scale adopted in Rowland's map of the sun, as well as below the degree of accuracy attained at Potsdam by photography in a part of the spectrum for the brighter stars. Increase of resolving power very frequently breaks up into groups, in the spectra of the sun and stars, the lines which had been regarded as single, and their supposed coincidences with terrestrial lines fall to the ground. For this reason many of the early conclusions, based on observations as good as it was possible to make at the time with the less powerful spectroscopes then in use, may not be found to be maintained under the much greater resolving power of modern instruments.

The spectroscope has failed as yet to interpret for us the remarkable spectrum of the Aurora Borealis. Undoubtedly in this phenomenon portions of our atmosphere are lighted up by electric discharges; we should expect, therefore, to recognise the spectra of the gases known to be present in it. As yet we have not been able to obtain similar spectra from these gases artificially, and especially we do not know the origin of the principal line in the green, which often appears alone, and may have therefore an origin independent of that of the other lines. Recently the suggestion has been made that the Aurora is a phenomenon produced by the dust of meteors and falling stars, and that near positions of certain auroral lines to lines or flutings of manganese, lead, barium, thallium, iron, etc., are sufficient to justify us in regarding meteoric dust in the atmosphere as the origin of the auroral spectrum. Liveing and

Dewar have made a conclusive research on this point, by availing themselves of the dust of excessive minuteness thrown off from the surface of electrodes of various metals and meteorites by a disruptive discharge, and carried forward into the tube of observation by a more or less rapid current of air or other gas. These experiments prove that metallic dust, however fine, suspended in a gas will not act like gaseous matter in becoming luminous with its characteristic spectrum in an electric discharge, similar to that of the Aurora. Professor Schuster has suggested that the principal line may be due to some very light gas which is present in too small a proportion to be detected by chemical analysis or even by the spectroscope in the presence of the other gases near the earth, but which at the height of the auroral discharges is in a sufficiently greater relative proportion to give a spectrum. Lemström, indeed, states that he saw this line in the silent discharge of a Holtz machine on a mountain in Lapland. The lines may not have been obtained in our laboratories from the atmospheric gases, on account of the difficulty of reproducing in tubes with sufficient nearness the conditions under which the auroral discharges take place.

In the spectra of comets the spectroscope has shown the presence of carbon presumably in combination with hydrogen, and also sometimes with nitrogen; and in the case of comets approaching very near the sun, the lines of sodium, and other lines which have been supposed to belong to iron. Though the researches of Professor H. A. Newton and of Professor Schiaparelli leave no doubt of the close connection of comets with corresponding periodic meteor swarms, and therefore of the probable identity of cometary matter with that of meteorites, with which the spectroscopic evidence agrees, it would be perhaps unwise at present to attempt to define too precisely the exact condition of the matter which forms the nucleus of the comet. In any case the part of the light of the comet which is not reflected solar light can scarcely be attributed to a high temperature produced by the clashing of separate meteoric stones set up within the nucleus by the sun's disturbing force. We must look rather to disruptive electric discharges produced probably by processes of evaporation due to increased solar heat, which would be amply sufficient to set free portions of the occluded gases into the vacuum of space. May it be that these discharges are assisted, and indeed possibly increased, by the recently discovered action of the ultra-violet part of the sun's light? Hertz has shown that ultra-violet light can produce a discharge from a negatively electrified piece of metal, while Hallwachs and Righi have shown further that ultra-violet light can even charge positively an unelectrified piece of metal; phenomena which Lenard and Wolf associate with the disengagement from the metallic surfaces of very minute particles. Similar actions on cometary matter, un-screened as it is by an absorptive atmosphere, at least of any noticeable

extent, may well be powerful when a comet approaches the sun, and help to explain an electrified condition of the evaporated matter which would possibly bring it under the sun's repulsive action. We shall have to return to this point in speaking of the solar corona.

A very great advance has been made in our knowledge of the constitution of the sun by the recent work at the Johns Hopkins University by means of photography and concave gratings, in comparing the solar spectrum, under great resolving power, directly with the spectra of the terrestrial elements. Professor Rowland has shown that the lines of thirty-six terrestrial elements at least are certainly present in the solar spectrum, while eight others are doubtful. Fifteen elements, including nitrogen as it shows itself under an electric discharge in a vacuum tube, have not been found in the solar spectrum. Some ten other elements, inclusive of oxygen, have not yet been compared with the sun's spectrum.

Rowland remarks that of the fifteen elements named as not found in the sun, many are so classed because they have few strong lines, or none at all, in the limit of the solar spectrum as compared by him with the arc. Boron has only two strong lines. The lines of bismuth are compound and too diffuse. Therefore even in the case of these fifteen elements there is little evidence that they are really absent from the sun.

It follows that if the whole earth were heated to the temperature of the sun, its spectrum would resemble very closely the solar spectrum.

Rowland has not found any lines common to several elements, and in the case of some accidental coincidences, more accurate investigation reveals some slight difference of wave-length or a common impurity. Further, the relative strength of the lines in the solar spectrum is generally, with a few exceptions, the same as that in the electric arc, so that Rowland considers that his experiments show "very little evidence" of the breaking up of the terrestrial elements in the sun.

Stas in a recent paper gives the final results of eleven years of research on the chemical elements in a state of purity, and on the possibility of decomposing them by the physical and chemical forces at our disposal. His experiments on calcium, strontium, lithium, magnesium, silver, sodium and thallium, show that these substances retain their individuality under all conditions, and are unalterable by any forces that we can bring to bear upon them.

Professor Rowland looks to the solar lines which are unaccounted for as a means of enabling him to discover such new terrestrial elements as still lurk in rare minerals and earths, by confronting their spectra directly with that of the sun. He has already resolved yttrium spectroscopically into three components, and actually into two. The comparison of the results of this independent analytical method with the remarkable but different conclusions to which M. Lecoq

de Boisbaudran and Mr. Crookes have been led respectively, from spectroscopic observation of these bodies when glowing under molecular bombardment in a vacuum tube, will be awaited with much interest. It is worthy of remark that as our knowledge of the spectrum of hydrogen in its complete form came to us from the stars, it is now from the sun that chemistry is probably about to be enriched by the discovery of new elements.

In a discussion in the Bakerian Lecture for 1885 of what we knew up to that time of the sun's corona, I was led to the conclusion that the corona is essentially a phenomenon similar in the cause of its formation to the tails of comets—namely, that it consists for the most part probably of matter going from the sun under the action of a force, possibly electrical, which varies as the surface, and can therefore in the case of highly attenuated matter easily master the force of gravity even near the sun. Though many of the coronal particles may return to the sun, those which form the long rays or streamers do not return; they separate and soon become too diffused to be any longer visible, and may well go to furnish the matter of the zodiacal light, which otherwise has not received a satisfactory explanation. And further, if such a force exist at the sun, the changes of terrestrial magnetism may be due to direct electric action, as the earth moves through lines of inductive force.*

These conclusions appear to be in accordance broadly with the lines along which thought has been directed by the results of subsequent eclipses. Professor Schuster takes an essentially similar view, and suggests that there may be a direct electric connection between the sun and the planets. He asks further whether the sun may not act like a magnet in consequence of its revolution about its axis. Professor Bigelow has recently treated the coronal forms by the theory of spherical harmonics, on the supposition that we see phenomena similar to those of free electricity, the rays being lines of force, and the coronal matter discharged from the sun, or at least arranged or controlled by these forces. At the extremities of the streams for some reasons the repulsive power may be lost, and gravitation set in, bringing the matter back to the sun. The matter which does leave the sun is persistently transported to the equatorial plane of the corona; in fact, the zodiacal light may be the accumulation at great distances from the sun along this equator of such-like material. Photographs on a larger scale will be desirable for the full development of the conclusions which may follow from this study of the curved forms of the coronal structure. Professor Schaeberle, however, considers that the coronal phenomena may be satisfactorily accounted for on the supposition that the corona is formed of streams of matter ejected mainly from the spot zones with great initial velocities, but smaller than 382 miles a second. Further, that the different types of the corona are due to the effects of

* See p. 347, footnote.

perspective on the streams from the earth's place at the time relatively to the plane of the solar equator.

Of the physical and the chemical nature of the coronal matter we know very little. Schuster concludes, from an examination of the eclipses of 1882, 1883, and 1886, that the continuous spectrum of the corona has the maximum of actinic intensity displaced considerably towards the red when compared with the spectrum of the sun, which shows that it can only be due in small part to solar light scattered by small particles. The lines of calcium and of hydrogen do not appear to form part of the normal spectrum of the corona. The green coronal line has no known representative in terrestrial substances, nor has Schuster been able to recognise any of our elements in the other lines of the corona.

The spectra of the stars are almost infinitely diversified, yet they can be arranged with some exceptions in a series in which the adjacent spectra, especially in the photographic region, are scarcely distinguishable, passing from the bluish-white stars like Sirius, through stars more or less solar in character, to stars with banded spectra, which divide themselves into two apparently independent groups, according as the stronger edge of the bands is towards the red or the blue. In such an arrangement the sun's place is towards the middle of the series.

At present a difference of opinion exists as to the direction in the series in which evolution is proceeding, whether by further condensation white stars pass into the orange and red stages, or whether these more coloured stars are younger and will become white by increasing age. The latter view was suggested by Johnstone Stoney in 1867.

About ten years ago Ritter, in a series of papers, discussed the behaviour of gaseous masses during condensation, and the probable resulting constitution of the heavenly bodies. According to him, a star passes through the orange and red stages twice—first during a comparatively short period of increasing temperature which culminates in the white stage, and a second time during a more prolonged stage of gradual cooling. He suggested that the two groups of banded stars may correspond to these different periods: the young stars being those in which the stronger edge of the dark band is towards the blue, the other banded stars, which are relatively less luminous and few in number, being those which are approaching extinction through age.

Recently a similar evolutional order has been suggested, which is based upon the hypothesis that the nebulae and stars consist of colliding meteoric stones in different stages of condensation.

More recently the view has been put forward that the diversified spectra of the stars do not represent the stages of an evolutional progress, but are due for the most part to differences of original constitution.

The few minutes which can be given to this part of the address are insufficient for a discussion of these different views. I purpose, therefore, to state briefly, and with reserve, as the subject is obscure, some of the considerations from the characters of their spectra which appeared to me to be in favour of the evolutional order in which I arranged the stars from their photographic spectra in 1879. This order is essentially the same as Vogel had previously proposed in his classification of the stars in 1874, in which the white stars, which are most numerous, represent the early adult and most persistent stage of stellar life, the solar condition that of full maturity and of commencing age; while in the orange and red stars with banded spectra we see the setting in and advance of old age. But this statement must be taken broadly, and not as asserting that all stars, however different in mass and possibly to some small extent in original constitution, exhibit one invariable succession of spectra.

In the spectra of the white stars the dark metallic lines are relatively inconspicuous, and occasionally absent, at the same time that the dark lines of hydrogen are usually strong, and more or less broad, upon a continuous spectrum, which is remarkable for its brilliancy at the blue end. In some of these stars the hydrogen and some other lines are bright, and sometimes variable.

As the greater or less prominence of the hydrogen lines, dark or bright, is characteristic of the white stars as a class, and diminishes gradually with the incoming and increase in strength of the other lines, we are probably justified in regarding it as due to some conditions which occur naturally during the progress of stellar life, and not to a peculiarity of original constitution.

To produce a strong absorption-spectrum a substance must be at the particular temperature at which it is notably absorptive; and, further, this temperature must be sufficiently below that of the region behind from which the light comes for the gas to appear, so far as its special rays are concerned, as darkness upon it. Considering the high temperature to which hydrogen must be raised before it can show its characteristic emission and absorption, we shall probably be right in attributing the relative feebleness or absence of the other lines, not to the paucity of the metallic vapours, but rather to their being so hot relatively to the substances behind them as to show feebly, if at all, by reversion. Such a state of things would more probably be found, it seems to me, in conditions anterior to the solar stage. A considerable cooling of the sun would probably give rise to banded spectra due to compounds, or to more complex molecules, which might form near the condensing points of the vapours.

The sun and stars are generally regarded as consisting of glowing vapours surrounded by a photosphere where condensation is taking place, the tem-

perature of the photospheric layer from which the greater part of the radiation comes being constantly renewed from the hotter matter within.

At the surface the convection currents would be strong, producing a considerable commotion, by which the different gases would be mixed and not allowed to retain the inequality of proportions at different levels due to their vapour densities.

Now the conditions of the radiating photosphere and those of the gases above it, on which the character of the spectrum of a star depends, will be determined, not alone by temperature, but also by the force of gravity in these regions; this force will be fixed by the star's mass and its stage of condensation, and will become greater as the star continues to condense.

In the case of the sun the force of gravity has already become so great at the surface that the decrease of the density of the gases must be extremely rapid, passing in the space of a few miles from atmospheric pressure to a density infinitesimally small; consequently the temperature-gradient at the surface, if determined solely by expansion, must be extremely rapid. The gases here, however, are exposed to the fierce radiation of the sun, and unless wholly transparent, would take up heat, especially if any solid or liquid particles were present from condensation or convection currents.

From these causes, within a very small extent of space at the surface of the sun, all bodies with which we are acquainted should fall to a condition in which the extremely tenuous gas could no longer give a visible spectrum. The insignificance of the angle subtended by this space as seen from the earth should cause the boundary of the solar atmosphere to appear defined. If the boundary which we see be that of the sun proper, the matter above it will have to be regarded as in an essentially dynamical condition—an assemblage, so to speak, of gaseous projectiles for the most part falling back upon the sun after a greater or less range of flight. But in any case it is within a space of relatively small extent in the sun, and probably in the other solar stars, that the reversion which is manifested by dark lines is to be regarded as taking place.

Passing backward in the star's life, we should find a gradual weakening of gravity at the surface, a reduction of the temperature-gradient so far as it was determined by expansion, and convection currents of less violence producing less interference with the proportional quantities of gases due to their vapour densities, while the effects of eruptions would be more extensive.

At last we might come to a state of things in which, if the star were hot enough, only hydrogen might be sufficiently cool relatively to the radiation behind to produce a strong absorption. The lower vapours would be protected, and might continue to be relatively too hot for their lines to appear very dark upon the continuous spectrum; besides, their lines might be possibly to some

extent effaced by the coming in under such conditions in the vapours themselves of a continuous spectrum.

In such a star the light radiated towards the upper part of the atmosphere may have come from portions lower down of the atmosphere itself, or at least from parts not greatly hotter. There may be no such great difference of temperature of the low and less low portions of the star's atmosphere as to make the darkening effect of absorption of the protected metallic vapours to prevail over the illuminating effect of their emission.

It is only by a vibratory motion corresponding to a very high temperature that the bright lines of the first spectrum of hydrogen can be brought out, and by the equivalence of absorbing and emitting power that the corresponding spectrum of absorption should be produced ; yet for a strong absorption to show itself, the hydrogen must be cool relatively to the source of radiation behind it, whether this be condensed particles or gas. Such conditions, it seems to me, should occur in the earlier rather than in the more advanced stages of condensation.

The subject is obscure, and we may go wrong in our mode of conceiving of the probable progress of events, but there can be no doubt that in one remarkable instance the white-star spectrum is associated with an early stage of condensation.

Sirius is one of the most conspicuous examples of one type of this class of stars. Photometric observations combined with its ascertained parallax show that this star emits from forty to sixty times the light of our sun, even to the eye, which is insensible to ultra-violet light, in which Sirius is very rich ; while we learn from the motion of its companion that its mass is not much more than double that of our sun. It follows that, unless we attribute to this star an improbably great emissive power, it must be of immense size, and in a much more diffuse and therefore an earlier condition than our sun ; though probably at a later stage than those white stars in which the hydrogen lines are bright.

A direct determination of the relative temperature of the photospheres of the stars might possibly be obtained in some cases from the relative position of maximum radiation of their continuous spectra. Langley has shown that through the whole range of temperature on which we can experiment, and presumably at temperatures beyond, the maximum of radiation-power in solid bodies gradually shifts upwards in the spectrum from the infra-red through the red and orange, and that in the sun it has reached the blue.

The defined character as a rule of the stellar lines of absorption suggests that the vapours producing them do not at the same time exert any strong power of general absorption. Consequently we should probably not go far wrong, when the photosphere consists of liquid or solid particles, if we could

compare select parts of the continuous spectrum between the stronger lines or where they are fewest. It is obvious that if extended portions of different stellar spectra were compared, their true relation would be obscured by the line-absorption.

The increase of temperature, as shown by the rise in the spectrum of the maximum of radiation, may not always be accompanied by a corresponding greater brightness of a star as estimated by the eye, which is an extremely imperfect photometric instrument. Not only is the eye blind to large regions of radiation, but even for the small range of light that we can see the visual effect varies enormously with its colour. According to Professor Langley, the same amount of energy which just enables us to perceive light in the crimson at A would in the green produce a visual effect 100,000 times greater. In the violet the proportional effect would be 1,600, in the blue 62,000, in the yellow 28,000, in the orange 14,000, and in the red 1,200. Captain Abney's recent experiments make the sensitiveness of the eye for the green near F to be 750 times greater than for the red about C. It is for this reason, at least in part, that I suggested in 1864, and have since shown by direct observation, that the spectrum of the nebula in Andromeda, and presumably of similar nebulæ, is, in appearance only, wanting in the red.

The stage at which the maximum radiation is in the green, corresponding to the eye's greatest sensitiveness, would be that in which it could be most favourably measured by eye-photometry. As the maximum rose into the violet and beyond, the star would increase in visual brightness, but not in proportion to the increase of energy radiated by it.

The brightness of a star would be affected by the nature of the substance by which the light was chiefly emitted. In the laboratory solid carbon exhibits the highest emissive power. A stellar stage in which radiation comes, to a large extent, from a photosphere of the solid particles of this substance, would be favourable for great brilliancy. Though the stars are built up of matter essentially similar to that of the sun, it does not follow that the proportion of the different elements is everywhere the same. It may be that the substances condensed in the photospheres of different stars may differ in their emissive powers, but probably not to a great extent.

All the heavenly bodies are seen by us through the tinted medium of our atmosphere. According to Langley, the solar stage of stars is not really yellow, but, even as gauged by our imperfect eyes, would appear bluish white if we could free ourselves from the deceptive influences of our surroundings.

From these considerations it follows that we can scarcely infer the evolutional stages of the stars from a simple comparison of their eye-magnitudes. We should expect the white stars to be, as a class, less dense than the stars in the solar stage. As great mass might bring in the solar type of spectrum

at a relatively earlier time, some of the brightest of these stars may be very massive and brighter than the sun—for example, the brilliant star Arcturus. For these reasons the solar stars should not only be denser than the white stars, but perhaps, as a class, surpass them in mass and eye-brightness.

It has been shown by Lane that, so long as a condensing gaseous mass remains subject to the laws of a purely gaseous body, its temperature will continue to rise.

The greater or less breadth of the lines of absorption of hydrogen in the white stars may be due to variations of the depth of the hydrogen in the line of sight, arising from the causes which have been discussed. At the sides of the lines the absorption and emission are feebler than in the middle, and would come out more strongly with a greater thickness of gas.

The diversities among the white stars are nearly as numerous as the individuals of the class. Time does not permit me to do more than to record that, in addition to the three sub-classes into which they have been divided by Vogel, Scheiner has recently investigated minor differences as suggested by the character of the third line of hydrogen near G. He has pointed out, too, that so far as his observations go the white stars in the constellation of Orion stand alone, with the exception of Algol, in possessing a dark line in the blue which has apparently the same position as a bright line in the Great Nebula of the same constellation; and Pickering finds in his photographs of the spectra of these stars dark lines corresponding to the principal lines of the bright-line stars and the planetary nebulae with the exception of the chief nebular line. The association of white stars with nebular matter in Orion, in the Pleiades, in the region of the Milky Way, and in other parts of the heavens, may be regarded as falling in with the view that I have taken.

In the stars possibly further removed from the white class than our sun, belonging to the first division of Vogel's third class, which are distinguished by absorption bands with their stronger edge towards the blue, the hydrogen lines are narrower than in the solar spectrum. In these stars the density-gradient is probably still more rapid, the depth of hydrogen may be less, and possibly the hydrogen molecules may be affected by a larger number of encounters with dissimilar molecules. In some red stars with dark hydrocarbon bands the hydrogen lines have not been certainly observed; if they are really absent, it may be because the temperature has fallen below the point at which hydrogen can exert its characteristic absorption; besides, some hydrogen will have united with the carbon. The coming in of the hydrocarbon bands may indicate a later evolutional stage, but the temperature may still be high, as acetylene can exist in the electric arc.

A number of small stars more or less similar to those which are known by the names of their discoverers, Wolf and Rayet, have been found by

Pickering in his photographs. These are remarkable for several brilliant groups of bright lines, including frequently the hydrogen lines and the line D₃, upon a continuous spectrum strong in blue and violet rays, in which are also dark lines of absorption. As some of the bright groups appear in his photographs to agree in position with corresponding bright lines in the planetary nebulae, Pickering suggests that these stars should be placed in one class with them, although the brightest nebular line is absent from these stars. The simplest conception of their nature would be that each star is surrounded by a nebula, the bright groups being due to the gaseous matter outside the star. Mr. Roberts, however, has not been able to bring out any indication of nebulosity by prolonged exposure. The remarkable star η Argus may belong to this class of the heavenly bodies.

In the nebulae, the elder Herschel saw portions of the fiery mist or "shining fluid" out of which the heavens and the earth had been slowly fashioned. For a time this view of the nebulae gave place to that which regarded them as external galaxies, cosmical "sandheaps," too remote to be resolved into separate stars; though indeed in 1858 Mr. Herbert Spencer showed that the observations of nebulae up to that time were really in favour of an evolutional progress.

In 1864 I brought the spectroscope to bear upon them; the bright lines which flashed upon the eye showed the source of the light of a number of them to be glowing gas, and so restored these bodies to what is probably their true place, as an early stage of sidereal life.

At that early time our knowledge of stellar spectra was small. For this reason partly, and probably also under the undue influence of theological opinions then widely prevalent, I unwisely wrote in my original paper in 1864, "that in these objects we no longer have to do with a special modification of our own type of sun, but find ourselves in presence of objects possessing a distinct and peculiar plan of structure." Two years later, however, in a lecture before this Association, I took a truer position. "Our views of the universe," I said, "are undergoing important changes; let us wait for more facts, with minds unfettered by any dogmatic theory, and therefore free to receive the teaching, whatever it may be, of new observations."

Let us turn aside for a moment from the nebulae in the sky to the conclusions to which philosophers had been irresistibly led by a consideration of the features of the solar system. We have before us in the sun and planets obviously not a haphazard aggregation of bodies, but a system resting upon a multitude of relations pointing to a common physical cause. From these considerations Kant and Laplace formulated the nebular hypothesis, resting it on gravitation alone, for at that time the science of the conservation of energy

was practically unknown. These philosophers showed how, on the supposition that the space now occupied by the solar system was once filled by a vaporous mass, the formation of the sun and planets could be reasonably accounted for.

By a totally different method of reasoning, modern science traces the solar system backward step by step to a similar state of things at the beginning. According to Helmholtz, the sun's heat is maintained by the contraction of his mass, at the rate of about 220 feet a year. Whether at the present time the sun is getting hotter or colder we do not certainly know. We can reason back to the time when the sun was sufficiently expanded to fill the whole space occupied by the solar system, and was reduced to a great glowing nebula. Though man's life, the life of the race perhaps, is too short to give us direct evidence of any distinct stages of so august a process, still the probability is great that the nebular hypothesis, especially in the more precise form given to it by Roche, does represent broadly, notwithstanding some difficulties, the succession of events through which the sun and planets have passed.

The nebular hypothesis of Laplace requires a rotating mass of fluid which at successive epochs became unstable from excess of motion, and left behind rings, or more probably perhaps lumps, of matter from the equatorial regions.

The difficulties to which I have referred have suggested to some thinkers a different view of things, according to which it is not necessary to suppose that one part of the system gravitationally supports another. The whole may consist of a congeries of discrete bodies, even if these bodies be the ultimate molecules of matter. The planets may have been formed by the gradual accretion of such discrete bodies. On the view that the material of the condensing solar system consisted of separate particles or masses, we have no longer the fluid pressure which is an essential part of Laplace's theory. Faye, in his theory of evolution from meteorites, has to throw over this fundamental idea of the nebular hypothesis, and he formulates instead a different succession of events in which the outer planets were formed last—a theory which has difficulties of its own.

Professor George Darwin has recently shown, from an investigation of the mechanical conditions of a swarm of meteorites, that on certain assumptions a meteoric swarm might behave as a coarse gas, and in this way bring back the fluid pressure exercised by one part of the system on the other, which is required by Laplace's theory. One chief assumption consists in supposing that such inelastic bodies as meteoric stones might attain the effective elasticity of a high order which is necessary to the theory through the sudden volatilisation of a part of their mass at an encounter, by which what is virtually a violent explosive is introduced between the two colliding stones. Professor Darwin is careful to point out that it must necessarily be obscure as to how a small

mass of solid matter can take up a very large amount of energy in a small fraction of a second.

Any direct indications from the heavens themselves, however slight, are of so great value, that I should perhaps in this connection call attention to a recent remarkable photograph by Mr. Roberts of the Great Nebula in Andromeda. On this plate we seem to have presented to us some stage of cosmical evolution on a gigantic scale. The photograph shows a sort of whirlpool disturbance of the luminous matter which is distributed in a plane inclined to the line of sight, in which a series of rings of bright matter separated by dark spaces, greatly foreshortened by perspective, surround a large undefined central mass. The parallax of this nebula has not been ascertained, but there can be little doubt that we are looking upon a system very remote, and therefore of a magnitude great beyond our power of adequate comprehension. The matter of this nebula, in whatever state it may be, appears to be distributed, as in so many other nebulae, in rings or spiral streams, and to suggest a stage in a succession of evolutional events not inconsistent with that which the nebular hypothesis requires. To liken this object more directly to any particular stage in the formation of the solar system would be "to compare things great with small," and might be, indeed, to introduce a false analogy; but on the other hand we should err through an excess of caution if we did not accept the remarkable features brought to light by this photograph as a presumptive indication of a progress of events in cosmical history following broadly upon the lines of Laplace's theory.

The old view of the original matter of the nebulae, that it consisted of a "fiery mist,"

"a tumultuous cloud
Instinct with fire and nitre,"

fell at once with the rise of the science of thermodynamics. In 1854 Helmholtz showed that the supposition of an original fiery condition of the nebulous stuff was unnecessary, since in the mutual gravitation of widely separated matter we have a store of potential energy sufficient to generate the high temperature of the sun and stars. We can scarcely go wrong in attributing the light of the nebulae to the conversion of the gravitational energy of shrinkage into molecular motion.

The idea that the light of comets and of nebulae may be due to a succession of ignited flashes of gas from the encounters of meteoric stones was suggested by Professor Tait, and was brought to the notice of this Association in 1871 by Sir William Thomson in his Presidential Address.

The spectrum of the bright-line nebulae is certainly not such a spectrum as we should expect from the flashing by collisions of meteorites similar to those which have been analysed in our laboratories. The strongest lines of

the substances which in the case of such meteorites would first show themselves—iron, sodium, magnesium, nickel, etc.—are not those which distinguish the nebular spectrum. On the contrary, this spectrum is chiefly remarkable for a few brilliant lines, very narrow and defined, upon a background of a faint continuous spectrum, which contains numerous bright lines, and probably some lines of absorption.

The two most conspicuous lines have not been interpreted; for though the second line falls near, it is not coincident with a strong double line of iron. It is hardly necessary to say that, though the near position of the brightest line to the bright double line of nitrogen, as seen in a small spectroscope in 1864, naturally suggested at that early time the possibility of the presence of this element in the nebulae, I have been careful to point out, to prevent misapprehension, that in more recent years the nitrogen line and subsequently a lead line have been employed by me solely as fiducial points of reference in the spectrum.

The third line we know to be the second line of the first spectrum of hydrogen. Mr. Keeler has seen the first hydrogen line in the red, and photographs show that this hydrogen spectrum is probably present in its complete form, or nearly so, as we first learnt to know it in the absorption spectrum of the white stars.

We are not surprised to find associated with it the line D_3 , near the position of the absent sodium lines, probably due to the atom of some unknown gas, which in the sun can only show itself in the outbursts of highest temperature, and for this reason does not reveal itself by absorption in the solar spectrum.

It is not unreasonable to assume that the two brightest lines, which are of the same order as the third line, are produced by substances of a similar nature, in which a vibratory motion corresponding to a very high temperature is also necessary. These substances, as well as that represented by the line D_3 , may be possibly some of the unknown elements which are wanting in our terrestrial chemistry between hydrogen and lithium, unless indeed D_3 be on the lighter side of hydrogen.

In the laboratory we must have recourse to the electric discharge to bring out the spectrum of hydrogen; but in a vacuum-tube, though the radiation may be great, from the relative fewness of the luminous atoms or molecules or from some other cause, the temperature of the gas as a whole may be low.

On account of the large extent of the nebulae, a comparatively small number of luminous molecules or atoms would probably be sufficient to make the nebulae as bright as they appear to us. On such an assumption the average temperature may be low, but the individual particles, which by their encounters are luminous, must have motions corresponding to a very high temperature, and in this sense be extremely hot.

In such diffuse masses, from the great mean length of free path, the encounters would be rare but correspondingly violent, and tend to bring about vibrations of comparatively short period, as appears to be the case if we may judge by the great relative brightness of the more refrangible lines of the nebular spectrum.

Such a view may perhaps reconcile the high temperature which the nebular spectrum undoubtedly suggests with the much lower mean temperature of the gaseous mass, which we should expect at so early a stage of condensation, unless we assume a very enormous mass; or that the matter coming together had previously considerable motion, or considerable molecular agitation.

If the hydrogen shown by the spectroscope in the nebulae and in the atmospheres of the stars is retained by these bodies, we should be able to assign approximately an inferior limit for the force of gravity at their surfaces; provided that we assume that the gas is in the uncombined state, and always exists in some greater proportion than in the free space about them.

The inquisitiveness of the human mind does not allow us to remain content with the interpretation of the present state of the cosmical masses, but suggests the question—

“What see’st thou else
In the dark backward and abysm of time?”

What was the original state of things? how has it come about that by the side of aging worlds we have nebulae in a relatively younger stage? Have any of them received their birth from dark suns, which have collided into new life, and so belong to a second- or later generation of the heavenly bodies?

During the short historic period, indeed, there is no record of such an event; still it would seem to be only through the collision of dark suns, of which the number must be increasing, that a temporary rejuvenescence of the heavens is possible, and by such ebbings and flowings of stellar life that the inevitable end to which evolution in its apparently uncompensated progress is carrying us can, even for a little, be delayed.

We cannot refuse to admit as possible such an origin for nebulae.

In considering, however, the formation of the existing nebulae we must bear in mind that, in the part of the heavens within our ken, the stars still in the early and middle stages of evolution exceed greatly in number those which appear to be in an advanced condition of condensation. Indeed, we find some stars which may be regarded as not far advanced beyond the nebular condition.

It may be that the cosmical bodies which are still nebulous owe the lateness of their development to some conditions of the part of space where

they occur, such as conceivably a greater original homogeneity, in consequence of which condensation began less early. In other parts of space condensation may have been still further delayed, or even have not yet begun. It is worthy of remark that these nebulae group themselves about the Milky Way, where we find a preponderance of the white-star type of stars, and almost exclusively the bright-line stars which Pickering associates with the planetary nebulae. Further, Dr. Gill concludes, from the rapidity with which they impress themselves upon the plate, that the fainter stars of the Milky Way also, to a large extent, belong to this early type of stars. At the same time other types of stars occur also over this region, and the red hydrocarbon stars are found in certain parts; but possibly these stars may be before or behind the Milky Way, and not physically connected with it.

If light matter be suggested by the spectrum of these nebulae, it may be asked further, as a pure speculation, whether in them we are witnessing possibly a later condensation of the light matter which had been left behind, at least in a relatively greater proportion, after the first growth of worlds into which the heavier matter condensed, though not without some entanglement of the lighter substances. The wide extent and great diffuseness of this bright-line nebulosity over a large part of the constellation of Orion may be regarded perhaps as pointing in this direction. The diffuse nebulous matter streaming round the Pleiades may possibly be another instance, though the character of its spectrum has not yet been ascertained.

In the planetary nebulae, as a rule, there is a sensible increase of the faint continuous spectrum, as well as a slight thickening of the bright lines towards the centre of the nebula, appearances which are in favour of the view that these bodies are condensing gaseous masses.

Professor G. Darwin, in his investigation of the equilibrium of a rotating mass of fluid, found, in accordance with the independent researches of Poincaré, that when a portion of the central body becomes detached through increasing angular velocity, the portion should bear a far larger ratio to the remainder than is observed in the planets and satellites of the solar system, even taking into account heterogeneity from the condensation of the parent mass.

Now this state of things, in which the masses, though not equal, are of the same order, does seem to prevail in many nebulae, and to have given birth to a large class of binary stars. Mr. See has recently investigated the evolution of bodies of this class, and points out their radical differences from the solar system in the relatively large mass-ratios of the component bodies, as well as in the high eccentricities of their orbits brought about by tidal friction, which would play a more important part in the evolution of such systems.

Considering the large number of these bodies, he suggests that the solar

system should perhaps no longer be regarded as representing celestial evolution in its normal form—

“A goodly Paterne to whose perfect mould
He fashioned them . . .”

but rather as modified by conditions which are exceptional.

It may well be that in the very early stages condensing masses are subject to very different conditions, and that condensation may not always begin at one or two centres, but sometimes set in at a large number of points, and proceed in the different cases along very different lines of evolution.

Besides its more direct use in the chemical analysis of the heavenly bodies, the spectroscope has given to us a great and unexpected power of advance along the lines of the older astronomy. In the future a higher value may, indeed, be placed upon this indirect use of the spectroscope than upon its chemical revelations.

By no direct astronomical methods could motions of approach or of recession of the stars be even detected, much less could they be measured. A body coming directly towards us or going directly from us appears to stand still. In the case of the stars we can receive no assistance from change of size or of brightness. The stars show no true disks in our instruments, and the nearest of them is so far off that if it were approaching us at the rate of a hundred miles in a second of time, a whole century of such rapid approach would not do more than increase its brightness by the one-fortieth part.

Still it was only too clear that, so long as we were unable to ascertain directly those components of the stars' motions which lie in the line of sight, the speed and direction of the solar motion in space, and many of the great problems of the constitution of the heavens, must remain more or less imperfectly known. Now the spectroscope has placed in our hands this power, which, though so essential, appeared almost in the nature of things to lie for ever beyond our grasp; it enables us to measure directly, and under favourable circumstances to within a mile per second, or even less, the speed of approach or of recession of a heavenly body. This method of observation has the great advantage for the astronomer of being independent of the distance of the moving body, and is therefore as applicable and as certain in the case of a body on the extreme confines of the visible universe, so long as it is bright enough, as in the case of a neighbouring planet.

Doppler had suggested as far back as 1841 that the same principle on which he had shown that a sound should become sharper or flatter if there were an approach or a recession between the ear and the source of the sound would apply equally to light; and he went on to say that the difference of

colour of some of the binary stars might be produced in this way by their motions. Doppler was right in that the principle is true in the case of light, but he was wrong in the particular conclusion which he drew from it. Even if we suppose a star to be moving with a sufficiently enormous velocity to alter sensibly its colour to the eye, no such change would actually be seen, for the reason that the store of invisible light beyond both limits of the visible spectrum, the blue and the red, would be drawn upon, and light-waves invisible to us would be exalted or degraded so as to take the place of those raised or lowered in the visible region, and the colour of the star would remain unchanged. About eight years later Fizeau pointed out the importance of considering the individual wave-lengths of which white light is composed. It is, indeed, Doppler's principle which underlies the early determination of the velocity of light by Roemer; but this method, in its converse form, can scarcely be regarded as of practical value for the motions in the line of sight of binary stars. As soon, however, as we had learned to recognise the lines of known substances in the spectra of the heavenly bodies, Doppler's principle became applicable as the basis of a new and most fruitful method of investigation. The measurement of the small shift of the celestial lines from their true positions, as shown by the same lines in the spectrum of a terrestrial substance, gives to us the means of ascertaining directly in miles per second the speed of approach or of recession of the heavenly body from which the light has come.

An account of the first application of this method of research to the stars, which was made in my observatory in 1868, was given by Sir Gabriel Stokes from this chair at the meeting at Exeter in 1869. The stellar motions determined by me were shortly after confirmed by Professor Vogel in the case of Sirius, and in case of other stars by Mr. Christie, now Astronomer Royal, at Greenwich; but, necessarily, in consequence of the inadequacy of the instruments then in use for so delicate an inquiry, the amounts of these motions were but approximate.

The method was shortly afterwards taken up systematically at Greenwich and at the Rugby Observatory. It is to be greatly regretted that, for some reasons, the results have not been sufficiently accordant and accurate for a research of such exceptional delicacy. On this account probably, as well as that the spectroscope at that early time had scarcely become a familiar instrument in the observatory, astronomers were slow in availing themselves of this new and remarkable power of investigation. That this comparative neglect of so truly wonderful a method of ascertaining what was otherwise outside our powers of observation has greatly retarded the progress of astronomy during the last fifteen years, is but too clearly shown by the brilliant results which within the last couple of years have followed fast upon the recent masterly

application of this method by photography at Potsdam, and by eye with the needful accuracy at the Lick Observatory. At last this use of the spectroscope has taken its true place as one of the most potent methods of astronomical research. It gives us the motions of approach and of recession, not in angular measures, which depend for their translation into actual velocities upon separate determinations of parallactic displacements, but at once in terrestrial units of distance.

This method of work will doubtless be very prominent in the astronomy of the near future, and to it probably we shall have to look for the more important discoveries in sidereal astronomy which will be made during the coming century.

In his recent application of photography to this method of determining celestial motions, Professor Vogel, assisted by Dr. Scheiner, considering the importance of obtaining the spectrum of as many stars as possible on an extended scale without an exposure inconveniently long, wisely determined to limit the part of the spectrum on the plate to the region for which the ordinary silver-bromide gelatine plates are most sensitive—namely, to a small distance on each side of G—and to employ as the line of comparison the hydrogen line near G, and recently also certain lines of iron. The most minute and complete mechanical arrangements were provided for the purpose of securing the absolute rigidity of the comparison spectrum relatively to that of the star, and for permitting temperature adjustments and other necessary ones to be made.

The perfection of these spectra is shown by the large number of lines, no fewer than 250 in the case of Capella, within the small region of the spectrum on the plate. Already the motions of about fifty stars have been measured with an accuracy, in the case of the larger number of them, of about an English mile per second.

At the Lick Observatory it has been shown that observations can be made directly by eye with an accuracy equally great. Mr. Keeler's brilliant success has followed in great measure from the use of the third and fourth spectra of a grating with 14,438 lines to the inch. The marvellous accuracy attainable in his hands on a suitable star is shown by observations on three nights of the star Arcturus, the largest divergence of his measures being not greater than six-tenths of a mile per second, while the mean of the three nights' work agreed with the mean of five photographic determinations of the same star at Potsdam to within one-tenth of an English mile. These are determinations of the motions of a sun so stupendously remote that even the method of parallax practically fails to fathom the depth of intervening space, and by means of light waves which have been, according to Elkin's nominal parallax, nearly two hundred years upon their journey.

Mr. Keeler with his magnificent means has accomplished a task which

I attempted in vain in 1874, with the comparatively poor appliances at my disposal, of measuring the motions in the line of sight of some of the planetary nebulae. As the stars have considerable motions in space it was to be expected that nebulae should possess similar motions, for the stellar motion must have belonged to the nebulae out of which they have been evolved. My instrumental means, limiting my power of detection to motions greater than twenty-five miles per second, were insufficient. Mr. Keeler has found in the examination of ten nebulae motions varying from two miles to twenty-seven miles, with one exceptional motion of nearly forty miles.

For the nebula of Orion, Mr. Keeler finds a motion of recession of about ten miles a second. Now this motion agrees closely with what it should appear to have from the drift of the solar system itself, so far as it has been possible at present to ascertain the probable velocity of the sun in space. This grand nebula, of vast extent and of extreme tenuity, is probably more nearly at rest relatively to the stars of our system than any other celestial object we know; still it would seem more likely that even here we have some motion, small though it may be, than that the motions of the matter of which it is formed were so absolutely balanced as to leave this nebula in the unique position of absolute immobility in the midst of whirling and drifting suns and systems of suns.

The spectroscopic method of determining celestial motions in the line of sight has recently become fruitful in a new but not altogether unforeseen direction, for it has, so to speak, given us a separating power far beyond that of any telescope the glass-maker and the optician could construct, and so enabled us to penetrate into mysteries hidden in stars apparently single, and altogether unsuspected of being binary systems. The spectroscope has not simply added to the list of the known binary stars, but has given to us for the first time a knowledge of a new class of stellar systems, in which the components are in some cases of nearly equal magnitude, and in close proximity, and are revolving with velocities greatly exceeding the planetary velocities of our system.

The K line in the photographs of Mizar, taken at the Harvard College Observatory, was found to be double at intervals of fifty-two days. The spectrum was therefore not due to a single source of light, but to the combined effect of two stars moving periodically in opposite directions in the line of sight. It is obvious that if two stars revolve round their common centre of gravity in a plane not perpendicular to the line of sight, all the lines in a spectrum common to the two stars will appear alternately single or double.

In the case of Mizar and the other stars to be mentioned, the spectroscopic observations are not as yet extended enough to furnish more than an approximate determination of the elements of their orbits.

Mizar especially, on account of its relatively long period—about 105 days—

needs further observations. The two stars are moving each with a velocity of about fifty miles a second, probably in elliptical orbits, and are about 143 millions of miles apart. The stars, of about equal brightness, have together a mass about forty times as great as that of our sun.

A similar doubling of the lines showed itself in the Harvard photographs of β Aurigæ at the remarkably close interval of almost exactly two days, indicating a period of revolution of about four days. According to Vogel's later observations, each star has a velocity of nearly seventy miles a second, the distance between the stars being little more than seven and a half millions of miles, and the mass of the system 4·7 times that of the sun. The system is approaching us at the speed of about sixteen miles a second.

The telescope could never have revealed to us double stars of this order. In the case of β Aurigæ, combining Vogel's distance with Pritchard's recent determination of the star's parallax, the greatest angular separation of the stars as seen from the earth would be 1-200th part of a second of arc, and therefore very far too small for detection by the largest telescopes. If we take the relation of aperture to separating power usually accepted, an object glass of about 8 feet in diameter would be needed to resolve this binary star. The spectroscope, which takes no note of distance, magnifies, so to speak, this minute angular separation 4,000 times; in other words, the doubling of the lines, which is the phenomenon that we have to observe, amounts to the easily measurable quantity of twenty seconds of arc.

There were known, indeed, variable stars of short period, which it had been suggested might be explained on the hypothesis of a dark body revolving about a bright sun in a few days, but this theory was met by the objection that no such systems of closely revolving suns were known to exist.

The Harvard photographs of which we have been speaking were taken with a slitless form of spectroscope, the prisms being placed, as originally by Fraunhofer, before the object-glass of the telescope. This method, though it possesses some advantages, has the serious drawback of not permitting a direct comparison of the star's spectrum with terrestrial spectra. It is obviously unsuited to a variable star like Algol, where one star only is bright, for in such a case there would be no doubling of the lines, but only a small shift to and fro in the spectrum of the lines of the bright star as it moved in its orbit alternately towards and from our system, which would need for its detection the fiducial positions of terrestrial lines compared directly with them.

For such observations the Potsdam spectrograph was well adapted. Professor Vogel found that the bright star of Algol did pulsate backwards and forwards in the visual direction in a period corresponding to the known variation of its light. The explanation which had been suggested for the star's variability, that it was partially eclipsed at regular intervals of 68·8 hours by a dark

companion large enough to cut off nearly five-sixths of its light, was therefore the true one. The dark companion, no longer able to hide itself by its obscurity, was brought out into the light of direct observation by means of its gravitational effects.

Seventeen hours before minimum Algol is receding at the rate of about $24\frac{1}{2}$ miles a second, while seventeen hours after minimum it is found to be approaching with a speed of about $28\frac{1}{2}$ miles. From these data, together with those of the variation of its light, Vogel found, on the assumption that both stars have the same density, that the companion, nearly as large as the sun, but with about one-fourth his mass, revolves with a velocity of about 55 miles a second. The bright star, of about twice the size and mass, moves about the common centre of gravity with a speed of about 26 miles a second. The system of the two stars, which are about $3\frac{1}{4}$ millions of miles apart, considered as a whole, is approaching us with a velocity of 2·4 miles a second. The great difference in luminosity of the two stars, not less than fifty times, suggests rather that they are in different stages of condensation, and dissimilar in density.

It is obvious that if the orbit of a star with an obscure companion is sufficiently inclined to the line of sight, the companion will pass above or below the bright star and produce no variation of its light. Such systems may be numerous in the heavens. In Vogel's photographs, Spica, which is not variable, by a small shifting of its lines reveals a backward and forward periodical pulsation due to orbital motion. As the pair whirl round their common centre of gravity, the bright star is sometimes advancing, at others receding. They revolve in about four days, each star moving with a velocity of about 56 miles a second in an orbit probably nearly circular, and possess a combined mass of rather more than $2\frac{1}{2}$ times that of the sun. Taking the most probable value for the star's parallax, the greatest angular separation of the stars would be far too small to be detected with the most powerful telescopes.

If in a close double star the fainter companion is of the white-star type, while the bright star is solar in character, the composite spectrum would be solar with the hydrogen lines unusually strong. Such a spectrum would in itself afford some probability of a double origin, and suggest the existence of a companion star.

In the case of a true binary star the orbital motions of the pair would reveal themselves in a small periodical swaying of the hydrogen lines relatively to the solar ones.

Professor Pickering considers that his photographs show ten stars with composite spectra; of these, five are known to be double. The others are: τ Persei, ζ Aurigæ, δ Sagittarii, 31 Ceti, and β Capricorni. Perhaps β Lyræ should be added to this list.

In his recent classical work on the rotation of the sun, Dunér has not only determined the solar rotation for the equator but for different parallels of latitude up to 75° . The close accordance of his results shows that these observations are sufficiently accurate to be discussed with the variation of the solar rotation for different latitudes, which had been determined by the older astronomical methods from the observations of the solar spots.

Though I have already spoken incidentally of the invaluable aid which is furnished by photography in some of the applications of the spectroscope to the heavenly bodies, the new power which modern photography has put into the hands of the astronomer is so great, and has led already, within the last few years, to new acquisitions of knowledge of such vast importance, that it is fitting that a few sentences should be specially devoted to this subject.

Photography is no new discovery, being about half a century old; it may excite surprise, and indeed possibly suggest some apathy on the part of astronomers, that though the suggestion of the application of photography to the heavenly bodies dates from the memorable occasion when, in 1839, Arago, announcing to the Académie des Sciences the great discovery of Niepce and Daguerre, spoke of the possibility of taking pictures of the sun and moon by the new process, yet that it is only within a few years that notable advances in astronomical methods and discovery have been made by its aid.

The explanation is to be found in the comparative unsuitability of the earlier photographic methods for use in the observatory. In justice to the early workers in astronomical photography, among whom Bond, De la Rue, J. W. Draper, Rutherford, Gould, hold a foremost place, it is needful to state clearly that the recent great successes in astronomical photography are not due to greater skill, nor, to any great extent, to superior instruments, but to the very great advantages which the modern gelatine dry plate possesses for use in the observatory over the methods of Daguerre, and even over the wet collodion film on glass, which, though a great advance on the silver plate, went but a little way towards putting into the hands of the astronomer a photographic surface adapted fully to his wants.

The modern silver-bromide gelatine plate, except for its grained texture, meets the needs of the astronomer at all points. It possesses extreme sensitiveness; it is always ready for use; it can be placed in any position; it can be exposed for hours; lastly, it does not need immediate development, and for this reason can be exposed again to the same object on succeeding nights, so as to make up by several instalments, as the weather may permit, the total time of exposure which is deemed necessary.

Without the assistance of photography, however greatly the resources of

genius might overcome the optical and mechanical difficulties of constructing large telescopes, the astronomer would have to depend in the last resource upon his eye. Now, we cannot by the force of continued looking bring into view an object too feebly luminous to be seen at the first and keenest moment of vision. But the feeblest light which falls upon the plate is not lost, but is taken in and stored up continuously. Each hour the plate gathers up 3,600 times the light-energy which is received during the first second. It is by this power of accumulation that the photographic plate may be said to increase, almost without limit, though not in separating power, the optical means at the disposal of the astronomer for the discovery or the observation of faint objects.

Two principal directions may be pointed out in which photography is of great service to the astronomer. It enables him within the comparatively short time of a single exposure to secure permanently with great exactness the relative positions of hundreds or even of thousands of stars, or the minute features of nebulæ or other objects, or the phenomena of a passing eclipse—tasks which by means of the eye and hand could only be accomplished, if at all, after a very great expenditure of time and labour. Photography puts it in the power of the astronomer to accomplish in the short span of his own life, and so enter into their fruition, great works which otherwise must have been passed on by him as a heritage of labour to succeeding generations.

The second great service which photography renders is not simply an aid to the powers the astronomer already possesses. On the contrary, the plate, by recording light-waves which are both too small and too large to excite vision in the eye, brings him into new regions of knowledge, such as the infra-red and the ultra-violet parts of the spectrum, which must have remained for ever unknown but for artificial help.

The present year will be memorable in astronomical history for the practical beginning of the Photographic Chart and Catalogue of the Heavens, which took their origin in an International Conference which met in Paris in 1887, by the invitation of M. l'Amiral Mouchez, Director of the Paris Observatory.

The richness in stars down to the ninth magnitude of the photographs of the comet of 1882 taken at the Cape Observatory under the superintendence of Dr. Gill, and the remarkable star charts of the Brothers Henry which followed two years later, astonished the astronomical world. The great excellence of these photographs, which was due mainly to the superiority of the gelatine plate, suggested to these astronomers a complete map of the sky, and a little later gave birth in the minds of the Paris astronomers to the grand enterprise of an International Chart of the Heavens. The actual beginning of the work this year is in no small degree due to the great energy and tact with which the Director of the Paris Observatory has conducted the initial steps, through the many delicate and difficult questions which have unavoidably presented

themselves in an undertaking which depends upon the harmonious working in common of many nationalities, and of no fewer than eighteen observatories in all parts of the world. The three years since 1887 have not been too long for the detailed organisation of this work, which has called for several elaborate preliminary investigations on special points in which our knowledge was insufficient, and which have been ably carried out by Professors Vogel and Bakhuyzen, Dr. Trépied, Dr. Scheiner, Dr. Gill, the Astronomer Royal, and others. Time also was required for the construction of the new and special instruments.

The decisions of the Conference in their final form provide for the construction of a great photographic chart of the heavens with exposures corresponding to forty minutes' exposure at Paris, which it is expected will reach down to stars of about the fourteenth magnitude. As each plate is to be limited to four square degrees, and as each star, to avoid possible errors, is to appear on two plates, over 22,000 photographs will be required. For the more accurate determination of the positions of the stars, a *réseau* with lines at distances of 5 mm. apart is to be previously impressed by a faint light upon the plate, so that the image of the *réseau* will appear together with the images of the stars when the plate is developed. This great work will be divided, according to their latitude, among eighteen observatories provided with similar instruments, though not necessarily constructed by the same maker. Those in the British dominions and at Tacubaya have been constructed by Sir Howard Grubb.

Besides the plates to form the great chart, a second set of plates for a catalogue is to be taken, with a shorter exposure, which will give stars to the eleventh magnitude only. These plates, by a recent decision of the Permanent Committee, are to be pushed on as actively as possible, though as far as may be practicable plates for the chart are to be taken concurrently. Photographing the plates for the catalogue is but the first step in this work, and only supplies the data for the elaborate measurements which have to be made, which are, however, less laborious than would be required for a similar catalogue without the aid of photography.

Already Dr. Gill has nearly brought to conclusion, with the assistance of Professor Kapteyn, a preliminary photographic survey of the Southern heavens.

With an exposure sufficiently long for the faintest stars to impress themselves upon the plate, the accumulating action still goes on for the brighter stars, producing a great enlargement of their images from optical and photographic causes. The question has occupied the attention of many astronomers whether it is possible to find a law connecting the diameters of these more or less over-exposed images with the relative brightness of the stars themselves. The answer will come out undoubtedly in the affirmative, though at present

the empirical formulae which have been suggested for this purpose differ from each other. Captain Abney proposes to measure the total photographic action, including density as well as size, by the obstruction which the stellar image offers to light.

A further question follows as to the relation which the photographic magnitudes of stars bear to those determined by eye. Visual magnitudes are the physiological expression of the eye's integration of that part of the star's light which extends from the red to the blue. Photographic magnitudes represent the plate's integration of another part of the star's light—namely, from a little below where the power of the eye leaves off in the blue, to where the light is cut off by the glass, or is greatly reduced by want of proper corrections when a refracting telescope is used. It is obvious that the two records are taken by different methods in dissimilar units of different parts of the star's light. In the case of certain coloured stars the photographic brightness is very different from the visual brightness; but in all stars changes, especially of a temporary character, may occur in the photographic or the visual region, unaccompanied by similar changes in the other part of the spectrum. For these reasons it would seem desirable that the two sets of magnitudes should be tabulated independently, and be regarded as supplementary of each other.

The determination of the distances of the fixed stars from the small apparent shift of their positions when viewed from widely separated positions of the earth in its orbit is one of the most refined operations of the observatory. The great precision with which this minute angular quantity, a fraction of a second of arc only, has to be measured, is so delicate an operation with the ordinary micrometer—though, indeed, it was with this instrument that the classical observations of Sir Robert Ball were made—that a special instrument, in which the measures are made by moving the two halves of a divided object-glass, known as a heliometer, has been pressed into this service, and quite recently, in the skilful hands of Dr. Gill and Dr. Elkin, has largely increased our knowledge in this direction.

It is obvious that photography might be here of great service, if we could rely upon measurements of photographs of the same stars taken at suitable intervals of time. Professor Pritchard, to whom is due the honour of having opened this new path, aided by his assistants, has proved by elaborate investigations that measures for parallax may be safely made upon photographic plates, with, of course, the advantages of leisure and repetition; and he has already by this method determined the parallax for twenty-one stars with an accuracy not inferior to that of values previously obtained by purely astronomical methods.

The remarkable successes of astronomical photography, which depend

upon the plate's power of accumulation of a very feeble light acting continuously through an exposure of several hours, are worthy to be regarded as a new revelation. The first chapter opened when, in 1880, Dr. Henry Draper obtained a picture of the nebula of Orion; but a more important advance was made in 1883, when Dr. Common, by his photographs, brought to our knowledge details and extensions of this nebula hitherto unknown. A further disclosure took place in 1885, when the Brothers Henry showed for the first time in great detail the spiral nebulosity issuing from the bright star Maia of the Pleiades, and shortly afterwards nebulous streams about the other stars of this group. In 1886 Mr. Roberts, by means of a photograph to which three hours' exposure had been given, showed the whole background of this group to be nebulous. In the following year Mr. Roberts more than doubled for us the great extension of the nebular region which surrounds the trapezium in the constellation of Orion. By his photographs of the great nebula in Andromeda, he has shown the true significance of the dark canals which had been seen by the eye. They are in reality spaces between successive rings of bright matter, which appeared nearly straight owing to the inclination in which they lie relatively to us. These bright rings surround an undefined central luminous mass. I have already spoken of this photograph.

Some recent photographs by Mr. Russell show that the great rift in the Milky Way in Argus, which to the eye is void of stars, is in reality uniformly covered with them. Also quite recently Mr. George Hale has photographed the solar prominences by means of a grating, making use of the lines H and K.

The heavens are richly but very irregularly inwrought with stars. The brighter stars cluster into well-known groups upon a background formed of an enlacement of streams and convoluted windings and intertwined spirals of fainter stars, which becomes richer and more intricate in the irregularly rifted zone of the Milky Way.

We, who form part of the emblazonry, can only see the design distorted and confused; here crowded, there scattered, at another place superposed. The groupings due to our position are mixed up with those which are real.

Can we suppose that each luminous point has no other relation to those near it than the accidental neighbourhood of grains of sand upon the shore, or of particles of the wind-blown dust of the desert? Surely every star, from Sirius and Vega down to each grain of the light-dust of the Milky Way, has its present place in the heavenly pattern from the slow evolving of its past. We see a system of systems, for the broad features of clusters and streams and spiral windings which mark the general design are reproduced in every part. The whole is in motion, each point shifting its position by miles every second, though from the august magnitude of their distances from us and from each other, it

is only by the accumulated movements of years or of generations that some small changes of relative position reveal themselves.

The deciphering of this wonderfully intricate constitution of the heavens will be undoubtedly one of the chief astronomical works of the coming century. The primary task of the sun's motion in space together with the motions of the brighter stars has been already put well within our reach by the spectroscopic method of the measurement of star-motions in the line of sight.

From other directions information is accumulating: from photographs of clusters and parts of the Milky Way, by Roberts in this country, Barnard at the Lick Observatory, and Russell at Sydney; from the counting of stars, and the detection of their configurations, by Holden and by Backhouse; from the mapping of the Milky Way by eye, at Parsonstown; from photographs of the spectra of stars, by Pickering at Harvard and in Peru; and from the exact portraiture of the heavens in the great international star chart which begins this year.

I have but touched upon some of the problems of the newer side of astronomy. Of the many others which would claim our attention if time permitted I may name the following. The researches of the Earl of Rosse on lunar radiation, and the work on the same subject and on the sun, by Langley. Observations of lunar heat with an instrument of his own invention by Mr. Boys; and observations of the variation of the moon's heat with its phase by Mr. Frank Very. The discovery of the ultra-violet part of the hydrogen spectrum, not in the laboratory, but from the stars. The confirmation of this spectrum by terrestrial hydrogen in part by H. W. Vogel, and in its all but complete form by Cornu, who found similar series in the ultra-violet spectra of aluminium and thallium. The discovery of a simple formula for the hydrogen series by Balmer. The important question as to the numerical spectral relationship of different substances, especially in connection with their chemical properties; and the further question as to the origin of the harmonic and other relations between the lines and the groupings of lines of spectra; on these points contributions during the past year have been made by Rudolt v. Kövesligethy, Ames, Hartley, Deslandres, Rydberg, Grünwald, Kayser and Runge, Johnstone Stoney, and others. The remarkable employment of interference phenomena by Professor Michelson for the determination of the size, and distribution of light within them, of the images of objects which when viewed in a telescope subtend an angle less than that subtended by the light-wave at a distance equal to the diameter of the objective. A method applicable not alone to celestial objects, but also to spectral lines, and other questions of molecular physics.

Along the older lines there has not been less activity; by newer methods by the aid of larger or more accurately constructed instruments, by greater

refinement of analysis, knowledge has been increased, especially in precision and minute exactness.

Astronomy, the oldest of the sciences, has more than renewed her youth. At no time in the past has she been so bright with unbounded aspirations and hopes. Never were her temples so numerous, nor the crowd of her votaries so great. The British Astronomical Association, formed within the year, numbers already about 600 members. Happy is the lot of those who are still on the eastern side of life's meridian!

Already, alas! the original founders of the newer methods are falling out—Kirchhoff, Ångström, D'Arrest, Secchi, Draper, Becquerel; but their places are more than filled; the pace of the race is gaining, but the goal is not and never will be in sight.

Since the time of Newton our knowledge of the phenomena of Nature has wonderfully increased, but man asks, perhaps more earnestly now than then, what is the ultimate reality behind the reality of the perceptions? Are they only the pebbles of the beach with which we have been playing? Does not the ocean of ultimate reality and truth lie beyond?

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