Philosophical Magazine Series 6

ISSN: 1941-5982 (Print) 1941-5990 (Online) Journal homepage: http://www.tandfonline.com/loi/tphm17

# XVIII. On the properties of the rays producing Aurora Borealis

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**To cite this article:** L. Vegard (1912) XVIII. On the properties of the rays producing Aurora Borealis , Philosophical Magazine Series 6, 23:134, 211-237, DOI: 10.1080/14786440208637215

**To link to this article:** http://dx.doi.org/10.1080/14786440208637215

Published online: 08 Jun 2010.

earlier— certainly several millions of years ago. Prestwich gave a somewhat different turn to Stapff's theory in ascribing the heat to dynamical movements in the granite; movements which might have been of somewhat later date. But this source of heat was almost certainly inadequate. It appears difficult to urge a better hypothesis than that of the radioactive origin of the heat in a granitic mass extending deeply beneath the tunnel.

Unfortunately no other similar instance can be cited. The temperature observations in the case of the Simplon tunnel suggest themselves. Prof. Lees has calculated that a small amount of radium in those rocks would produce little effect*. A complete estimate of the radioactivity of the Simplon rocks has yet to be made. In view of the recent work which has been done in my laboratory, I must conclude that the general means for the Simplon rocks, which I formerly arrived at, may suffer from the same unknown source of error which apparently affected some other contemporaneous experiments.

Dec. 15, 1911.

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## XVIII. *On the Properties of the Rays producing Aurora Borealis.* *By* L. Vegard, *Universitetsstipendiat, University of Christiania* †.

### *Introductory.*

1. WE are at the present time quite familiar with the idea that the sun is sending out electric rays of some sort, and that such a radiation is the primary cause of Aurora Borealis and most magnetic disturbances.

Professor Kr. Birkeland ‡ has worked on this hypothesis for about fifteen years, and through a great number of observations treated by Birkeland and his collaborators, as well as through a number of laboratory experiments, a new light has been thrown upon these phenomena, and the results obtained are most strongly in favour of the radiation theory.

The theoretical work of Professor C. Störmer § on the

* C. H. Lees, Roy. Soc. Proc. A. vol. lxxxiii. p. 344.

† Communicated by the Author. Read before the British Association, Portsmouth, September 1, 1911.

‡ Kr. Birkeland, *Archives des Sciences phys. et nat. Genève*, 1896; *Recherches sur les taches du Soleil*, &c., 1899; *Expédition Norvégienne de 1899–1900*, &c., 1901; The Norwegian Aurora Polaris Expedition, 1902–1903.

§ C. Störmer, *Christiania Videnskabsselskabs Skr., Math.-Nat. Kl.* No. 3 1904; *Archives des Sciences phys. et nat. Genève* [4] vol. xxiv. 1907.

orbits of electric rays exposed to the field of an elementary magnet, when applied to the sun and the earth, has also shown that the main features of the aurora and magnetic disturbances are simple consequences of the radiation hypothesis.

In fact I think that, all arguments collected and weighed, it will hardly be possible to doubt that electric radiation from the sun is the main cause of the phenomena in question. They show, however, a great variety of forms and variations, and further investigations will be required before we are able to follow each phenomenon into details, and, above all, we have at present no definite knowledge as to the *physical nature* of those solar rays which are engaged in the production of magnetic disturbances and the various forms of aurora borealis.

The determination of the nature of these rays will be of great importance, not only for the study of these most interesting terrestrial phenomena, but knowing the types of radiations we may obtain valuable information regarding the constitution of the sun.

It is my intention in this paper to give a contribution to the solution of the question regarding the physical nature of the electric radiation from the sun, by trying to show that certain auroral forms, especially the draperies, both as regards position, occurrence, structure, and form, are explained in a simple way by assuming that they are caused by $\alpha$-rays, or rays having essentially the same properties, while the assumption of a radiation of the $\beta$-ray type meets with great difficulties.

This $\alpha$-ray hypothesis was first announced by the writer in a note to 'Nature' *, and some further consequences have been drawn in a couple of notes recently published in *Archiv f. mat. og nat. Videnskab.*†

## *Properties of $\alpha$-Rays.*

2. Before proceeding to treat the auroral problem, let us first recall to our memory some of the most characteristic properties of $\alpha$-rays.

The $\alpha$-rays hitherto studied consist of helium atoms each of which carries an electric charge $+2e$.

The $\alpha$-rays sent out during a certain transformation process will start with a quite definite velocity. As shown by

* L. Vegard, 'Nature,' no. 2163, p. 212 (1911).

† L. Vegard, *Archiv f. mat. og nat. Videnskab.* No. 6 and No. 9 (1911).

Bragg and Kleeman *, $\alpha$-rays from a thin layer of radium bromide in radioactive equilibrium with its disintegration products, consist of a mixture of homogeneous groups corresponding to the various steps of transformation which are accompanied by the expulsion of $\alpha$-rays.

The way in which $\alpha$-rays are absorbed by matter is very characteristic for this type of radiation, and is very different from the law of absorption of $\beta$-rays.

Suppose a bundle of $\alpha$-particles strikes a homogeneous layer of matter. The $\alpha$-particle for the greatest length of its path will penetrate the matter in nearly straight-lined orbits, and only a comparatively small scattering takes place.

During the passage the velocity gradually diminishes, and after having traversed a certain thickness of matter called the range the $\alpha$-particle loses its power of ionizing and of producing photochemical effects, and stops.

Bragg and Kleeman † have determined the range for various groups of $\alpha$-radiation, and from the knowledge of the initial velocity we can find the relation between range and velocity. H. Geiger ‡ recently measured the velocity ($v$) of the $\alpha$-particle at different points of its path through matter, and found the following simple relation

$$v^3 = k(r - x), \quad \ldots \ldots \quad (1)$$

where $x$ is the thickness traversed and $r$ is very nearly equal to the range, and $k$ is independent of $x$ and $v$. If the various $\alpha$-rays merely differ with respect to velocity, the relation between initial velocity V and the range R in a certain substance would be

$$\mathrm{V}^3 = k\mathrm{R}. \quad \ldots \ldots \quad (2)$$

Bragg and Kleeman measured the relative amount of ionization produced by a homogeneous pencil of $\alpha$-rays per unit length at various points along its path, and found the ionization to increase as the velocity diminished, first slowly, then more rapidly, and it *assumed a very marked maximum close up to the point where the rays are stopped.* On the assumption that the ionization ($i$) per unit length of path is proportional to the loss of kinetic energy, Geiger finds from equation (1) that $i^3 = \dfrac{k}{r-x}$.

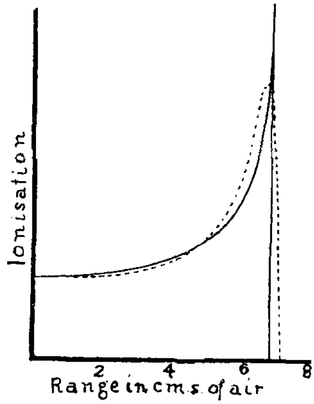
* Phil. Mag. [6] x. p. 318 (1905).

† *Loc. cit.*

‡ H. Geiger, Proc. Roy. Soc. A. lxxxiii. p. 505 (1910).

The theoretical and experimental curve is given in fig. 1, which is taken from Geiger's paper.

Fig. 1.




From observations of the absorption in various substances Bragg and Kleeman found that the masses of strata of equal absorption are proportional to the square root of the atomic weights.

Suppose we have a homogeneous layer of matter consisting of elements of atomic weight $A_1\, A_2 \ldots A_n$, then a stratum of total mass M per unit area has an absorbing power equivalent to a mass M′ of air given by the expression

$$M' = 3{\cdot}8\left(\frac{I_1}{\sqrt{A_1}} + \frac{I_2}{\sqrt{A_2}} + \ldots + \frac{I_n}{\sqrt{A_n}}\right)M, \quad . \quad (3)$$

where $I_1$ is the mass of the element $A_1$ for each unit of the total mass of the mixture.

H. Geiger * measured what he called the most probable scattering angle ($\lambda$) for the $\alpha$-rays, and found

$$\lambda = K_0\sqrt{A}X,$$

where X is the air equivalent traversed, and A the atomic weight. This result, when interpreted, shows that on an average the $\alpha$-particle will follow very nearly a straight line, the orbits will most of them only be slightly curved near the point where the particle stops, and consequently the track followed by a pencil of initially parallel rays will only very slightly broaden out from the track followed provided no scattering took place.

* H. Geiger, Proc. Roy. Soc. A. lxxxiii. p. 492 (1910).

## *Application to Aurora Borealis.*

### *The Structure of Auroræ.*

3. According to our present view, in the auroræ we are actually examining the luminosity produced when the electric radiation from the sun strikes the atmosphere, and from the form and structure of the luminosity we should be able to examine the way in which the solar radiation is absorbed by matter. In certain cases the form and structure is so characteristic and definite that we should be able to find out some definite properties with regard to the law of absorption of solar rays, and perhaps to identify them with some sort of known electric radiation.

One of the most conspicuous forms of aurora, showing very characteristic and definite properties, are no doubt the draperies.

Two drapery forms are represented in fig. 2; the one above

Fig. 2.

was observed at Godthaab, 1882, and the one below is from the classic work of P. Gaimard, 'Voyages en Scandinavie, en Laponie et au Feröe.'

We notice the straight-lined structure, so characteristic for these forms. The simplest interpretation possible of the straight-lined streamers is to suppose that they mark the track followed by the solar rays as they penetrate down the upper strata of the atmosphere. This interpretation is also in agreement with the fact that the streamers show a radiation point. We further notice that the straight-lined structure continues till the luminosity suddenly stops, forming a sharp edge of the drapery band.

In order to explain these straight-lined streamers, we must suppose *that the solar radiation producing them shows a very small scattering*, and we at once recognize one of the properties of $\alpha$-rays. On the other hand, if the draperies are at all formed as the effect of radiation penetrating down the atmosphere, it is impossible to explain their structure by assuming a radiation of the $\beta$-ray type.

As shown by Crowther *, the $\beta$-rays are scattered at a rate which is enormously greater than the rate at which they are absorbed. Thus the $\beta$-radiation would be spread out in all directions as soon as it entered into the atmosphere, long before it was absorbed in any appreciable amount. Consequently, the luminosity produced would broaden out and become diffuse, and *we should get no definite straight-lined streamers.*

The small scattering of the solar rays, and the impossibility of explaining the draperies by $\beta$-rays, is also evident from the extremely small thickness of the drapery bands. Adam Poulsen, observing at Godthaab, has examined the bands from the bottom edge in the direction of the streamers, and he states that they appeared as if they had only linear dimensions and no observable thickness.

The suddenness with which the luminosity stops at the end of the streamers shows that the solar rays quite suddenly lose their power of producing luminosity. In other words, if we were to observe the solar rays by the luminosity produced, we should find that *they possessed a well-defined range which in a striking way corresponds to the range of the $\alpha$-particles* as found from the ionization produced in a gas.

From the study of the discharge in rarified gases, we know that places showing great luminosity correspond to places where a great ionization takes place. The assumption is then a very legitimate one, that the luminosity produced by an $\alpha$-particle along its path follows the same law as the ionization. If so, *the maximum intensity of light at the edge of the band is simply explained if we suppose the ionization per unit length of path of the solar rays to follow a law essentially similar to that of $\alpha$-rays* (see fig. 1).

On examining and interpreting the structure of certain auroral forms, we have been able to show that the solar rays

* J. A. Crowther, Proc. Roy. Soc. A. lxxx. p. 186 (1908).

producing these forms, whatever their nature may be, have properties which are indeed most characteristic, and which are also found for $\alpha$-rays, or, in another way of expression, *by giving to the solar rays properties which are physically known from $\alpha$-rays we have succeeded in giving a simple explanation to a large class of auroral forms*, the explanation of which has so much puzzled earlier investigators in this field.

It would be premature, from these facts only, to identify the solar rays in question with $\alpha$-rays; but in view of the fact that the drapery forms must be produced by some kind of electric radiation which cannot be of the $\beta$-ray type, I think we may reason from similarity in properties to similarity in nature, and suppose that these solar rays consist of atoms or molecules carrying an electric charge. It will be a matter of further investigation to determine more definitely the kind of carrier and charge necessary for the production of the aurora belonging to the class considered showing suddenly stopping straight-lined streamers.

The similarity between the electric rays from the sun and the $\alpha$-rays makes it possible that at any rate certain forms of aurora may be produced by real $\alpha$-rays from radioactive substances, and it will be of considerable interest to draw the consequences of such an assumption to see how far the $\alpha$-ray hypothesis is in agreement with observed facts.

### *Absorption of $\alpha$-Rays by the Earth's Atmosphere. Height of Auroræ.*

4. We shall suppose the barometric pressure (B) given as a function of the height ($h$) above the ground. If we do not take into account the variation of gravity with the height, the mass of unit area of stratum going from the upper limit of the atmosphere to the height ($h$) is $s$.B, where B is given in cm. mercury of specific weight $s$. If this mass (M) consist of a mixture of substances its equivalent mass of air (M′) is found from equation (3). Provided the air equivalent is found corresponding to the height ($h$), equation (2) gives us the initial velocity of an $\alpha$-particle which would penetrate down to this height.

In the numerical calculations we shall use values of B given by Wegener *. These numbers are based on various assumptions, *e. g.* they depend on the assumptions we make with regard to the gases present. Thus the distribution of pressure, especially in the strata above 100 km. say, cannot

* *Phys. Zeitschr.* xii. Nos. 5 and 6 (1911).

claim great accuracy, but we shall use Wegener's numbers as probably being of the right order of magnitude.

The relation between velocity and height is calculated for the following two cases:—

1. The matter traversed is air, velocity $V_a$.
2. " " hydrogen, velocity $V_H$.

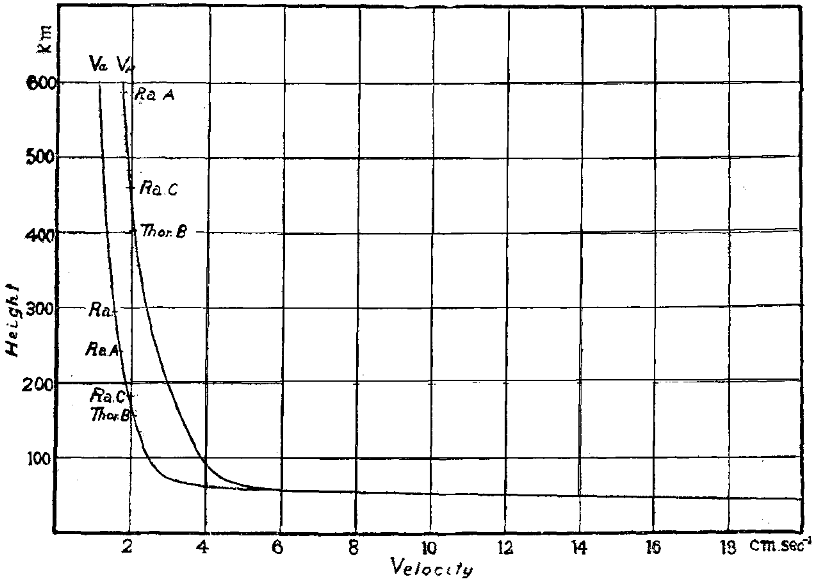
The results are given in the following table:—

TABLE I.

| $h$. | B. | $V_a$. | | $V_H$. | |
|---|---|---|---|---|---|
| km. | mm. | | cm./sec. | | cm./sec. |
| 500 | 0·00162 | 0·62 $V_0$ | $1·24\times10^9$ | 0·97 $V_0$ | $1·94\times10^9$ |
| 300 | 0·00329 | 0·79 " | 1·58 " | 1·24 " | 2·48 " |
| 200 | 0·00581 | 0·96 " | 1·92 " | 1·50 " | 3·0 " |
| 100 | 0·0128 | 1·24 " | 2·48 " | 1·94 " | 3·9 " |
| 60 | 0·106 | 1·51 " | 5·02 " | | |
| 20 | 41·7 | (18·4) " | (36·8) " | | |
| 0 | 760 | (48·4) " | (96·8) " | | |

$V_0$ is the velocity of $\alpha$-particles from Ra C, and is put equal to $2·0\times10^9$ cm. sec.$^{-1}$

Fig. 3.




The velocities corresponding to various values of ($h$) are illustrated in fig. 3. On each curve are marked a number of points corresponding to the range of the $\alpha$-rays given out by some known radioactive substances. We notice that down to a height of about 70 km. the value of $(h)$ diminishes rapidly with increase of velocity, so that $\alpha$-rays possessing a velocity about twice that of Ra C would get down to about 75 km.

Measurements of the height of auroræ have been made by a great many observers, and quite recently Störmer * has obtained measurements by means of a photographic method. Various observers give values which differ considerably; but it can be considered as quite certain that auroræ are most frequently found at a height interval, say, between 70 and 300 km. Störmer's observations gave a maximum of frequency at about 115 km. above the ground. Comparing calculated and observed values, we find *that the range of ordinary $\alpha$-rays in matter is of the right order of magnitude to explain the height of the main bulk of auroræ boreales.*

### *The Diurnal Distribution of Auroræ and its Bearing on the Radiation Theory.*

5. It has usually been held an indisputable fact that auroræ occur more frequently on the evening than on the morning side of the night. If there is such an asymmetry of distribution with respect to the plane through the sun and the magnetic axis, we might have a point of attack for the determination of the sign of the electric charge carried by the solar rays. Birkeland finds in the law of distribution stated an argument in favour of a negative radiation.

When the study of the structure of the auroræ led the writer to suppose a radiation of the $\alpha$-ray type, it became a question of importance to make further investigations into the distribution of auroræ, and, provided it followed the rule stated, to see whether it would involve the necessity for a negative charge.

In the following pages I have attempted to give the diurnal distribution of certain auroral forms, and also to compare results with theory so far as such coordination is possible at the present stage of theoretical investigation.

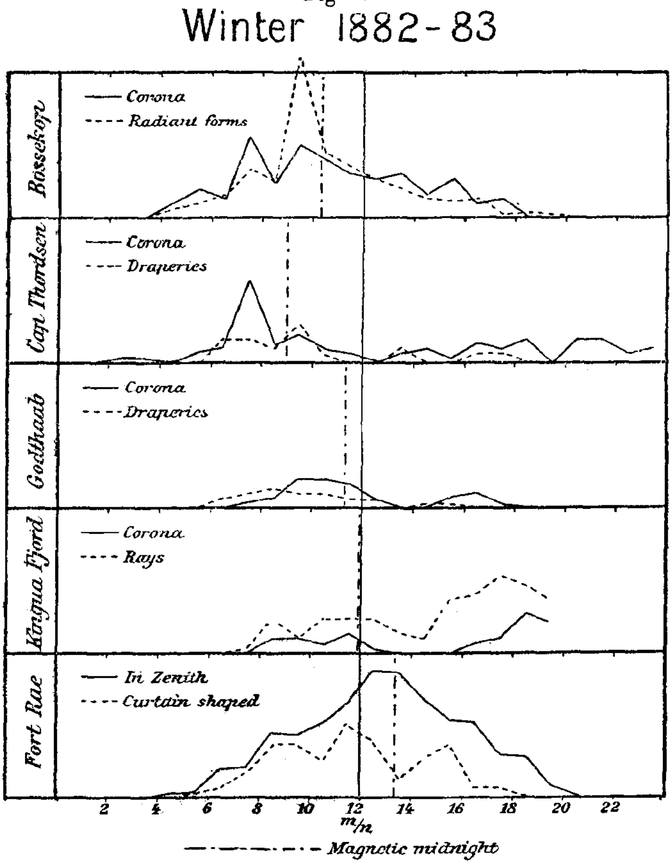
The determination of the diurnal distribution of aurora borealis meets with a great many difficulties. First of all, daylight will prevent auroræ from being observed during the day; secondly, the great variety of forms and intensities makes it very difficult to get a quantitative measure of auroræ which is free from any arbitrariness. Faults may also enter into the results from the sky being not equally well watched at different parts of the night.

* C. Störmer, *C. R.* 1911.

In dealing with the auroral problem I think we ought to be aware of the possibility that not all the luminous phenomena called northern lights are necessarily produced exactly in the same way and by the same agencies. Consequently, the diurnal variation may be different for different forms, and ought to be found for each type separately.

The types which mostly interest us in connexion with the $\alpha$-ray theory are those which we might call *radiant forms*, containing all types of aurora showing definite streamers ending suddenly with a maximum of luminosity. To this

Fig. 4.




group belong, *e. g.*, the draperies, the corona, rays and ray-bundles, a number of auroral bands, and probably some of the forms put down as arches may be merely distant aurora belonging to this group.

The apparent distribution of certain forms of aurora mostly belonging to this "radiant" group is given in Table II. and represented in fig. 4.

TABLE II.

| Local hour. | Bossekop. | | Cap Thordsen. | | Godthaab. | | Kingua Fjord. | | Fort Rae. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Corona. | Radiant Forms. | Corona. | Draperies. | Corona. | Draperies. | Corona. | Rays and Draperies. | Curtain-shaped. | In Zenith. |
| 1 ...... | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 ...... | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 ...... | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 ...... | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 ...... | 3 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| 6 ...... | 6 | 16 | 2 | 0 | 0 | 0 | 0 | 0 | 1 | 2 |
| 7 ...... | 4 | 22 | 3 | 5 | 0 | 2 | 0 | 0 | 2 | 12 |
| 8 ...... | 17 | 49 | 17 | 5 | 1 | 3 | 0 | 1 | 5 | 13 |
| 9 ...... | 7 | 37 | 4 | 3 | 2 | 4 | 3 | 7 | 11 | 27 |
| 10 ...... | 15 | 163 | 6 | 8 | 6 | 3 | 3 | 3 | 11 | 26 |
| 11 ...... | 12 | 67 | 3 | 2 | 6 | 3 | 2 | 7 | 8 | 31 |
| | 9 | 53 | 2 | 0 | 5 | 2 | 4 | 7 | 15 | 39 |
| m.n. 12 ...... | | | | | | | | | | |
| | 8 | 39 | 0 | 0 | 2 | 2 | 1 | 7 | 12 | 53 |
| 13 ...... | 9 | 31 | 2 | 3 | 0 | 0 | 0 | 4 | 4 | 52 |
| 14 ...... | 5 | 21 | 3 | 0 | 0 | 1 | 0 | 3 | 8 | 40 |
| 15 ...... | 8 | 18 | 1 | 0 | 2 | 1 | 0 | 11 | 11 | 32 |
| 16 ...... | 3 | 20 | 4 | 2 | 3 | 0 | 2 | 12 | 2 | 31 |
| 17 ...... | 4 | 5 | 3 | 2 | 1 | 1 | 3 | 16 | 2 | 18 |
| 18 ...... | 0 | 7 | 5 | 0 | 0 | 0 | 8 | 14 | 0 | 17 |
| 19 ...... | 0 | 4 | 1 | 0 | 0 | 0 | 6 | 11 | 0 | 5 |
| 20 ...... | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 21 ...... | 0 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 22 ...... | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 23 ...... | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

The results are deduced from observations recorded at various polar stations during the polar year 1882–83. The numbers in the second to eleventh columns give for hour-intervals the total number of auroræ of the form considered which have been observed from the beginning of October 1882 to the end of March 1883. The form is given one mark each time it is observed, provided the time-interval between successive observations is greater than 0·2 hour. Thus the type counted is never given more than one mark in an interval of 0·2 hour, even when the same type has been recorded several times during that same interval.

In spite of the disturbing influence of daylight, the curves for the distribution during the night-time show the existence of one well-marked evening maximum, and also for the corona and drapery forms a well-marked minimum just after midnight. In most cases we also find a morning maximum, which, however, is not very well marked; and although its existence can hardly be doubted, the determination of its time of occurrence is rendered difficult, partly from the small frequency of auroræ at this part of the night, partly from the fact that it occurs so late in the morning that the daylight may have a disturbing influence on its position.

In Table III. is given the position of the various stations and the occurrence of the evening maxima.

Table III.

| Station. | Latitude. | Longitude. | Form. | $r$. | Time of evening max. Each form. | Time of evening max. Mean. | $\alpha$. | $\delta_m$. |
|---|---|---|---|---|---|---|---|---|
| Bossekop ...... | 69° 57′ N. | 23° 15′ E. | Corona ............<br>Radiant forms ... | 2·0<br>2·9 | 9.0 P.M.<br>9.5 „ | P.M.<br>9.25 | 14°·5 | 5°·5 |
| Cap Thordsen. | 78° 28′ N. | 15° 42′ E. | Corona ............<br>Draperies ......... | 1·15<br>3·3 | 7.5 „<br>8.4 „ | 8.0 | 14°·5 | 4°·1 |
| Godthaab ...... | 64° 11′ N. | 51° 43′ W. | Corona ............<br>Draperies ......... | 2·5<br>3·4 | 10.3 „<br>9.3 „ | 9.8 | 22° | 20°·9 |
| Kingua Fjord. | 66° 36′ N. | 67° 15′ W. | Corona ............<br>Rays & Draperies. | 0·60<br>0·32 | 10.3 „<br>10.9 „ | 10.6 | 19°·1 | 24°·5 |
| Fort Rae ...... | 62° 39′ N. | 115° 44′ W. | Curtain-shaped ...<br>In Zenith ......... | 1·4<br>0·61 | 11.5 „<br>12·5 A.M. | 12.0 | 18°·9 | 22°·2 |

The quantity $r$ is the ratio between the number of auroræ observed before to those observed after midnight.

The curves show that auroræ are far from being equally distributed on both sides of midnight. This asymmetry cannot be accounted for by any disturbing influence of daylight, because this light effect would be symmetrical with respect to midnight. The values of $r$ show that at the three eastern stations, during the time of sufficient darkness, more auroræ of the forms considered appear on the evening side.

Kingua Fjord, however, occupies a most singular position in this respect; also here the auroræ show two maxima, but they occur with a decidedly greater frequency around the morning maximum than around that of the evening. This result is the more remarkable when it is compared with that of Godthaab. This station is situated very nearly on the same latitude as Kingua Fjord, and is not very far apart from it, and further, the observations at the two places cover the very same period.

Passing on to the most westerly station, Fort Rae, we find that the value of $r$ increases again. For the curtain form it is greater than one, and for auroræ through the zenith somewhat less than one; but this fact does not show, as in the case of Kingua Fjord, that more auroræ are found near the morning maximum; it is rather a consequence of the fact that the evening maximum occurs much later at this station than at the more easterly ones.

The evening maximum is seen to occur at very different local hours. At Cap Thordsen it occurs as early as 8 o'clock, while at Fort Rae it occurs at 12. The occurrence of the maxima at the various stations will become more regular when regarded in relation to the magnetic axis instead of the axis of rotation of the earth. Let on a geocentric sphere O be the position of the station, S that of the sun at the moment of the evening maximum, and P and P′ the points where the axis of rotation and the magnetic axis cut the sphere respectively.

The hour angle of the sun SPO is given by the local time of the occurrence of the maximum. The corresponding angle with reference to the magnetic axis is SP′O, and has been calculated for the various stations. The angle $\alpha$ given in Table III. is supplementary to SP′O or $\angle \mathrm{SP'O} = 180^\circ - \alpha$.

In Table III., $90^\circ + \delta_m$ is the angle between the north direction of the magnetic axis and the direction to the sun at the time of the evening maximum.

In spite of the great differences of the hour-angle OPS the angle SP′O comes out nearly constant. This will also be evident from fig. 4 (p. 220), where a line is drawn giving the time when the station cuts the plane through the sun and the magnetic axis, or, as we might call it, the time of *magnetic midnight*.

The values of $\alpha$ show that *for all stations the evening maximum for the winter* 1882–83 *occurred about* 1·3 *hours before magnetic midnight.*

We saw that auroræ did not occur symmetrically with regard to a plane through the sun and the axis of rotation. Looking at the curves, we notice that there is also a marked asymmetry with respect to the magnetic midnight, or with respect to a plane through the sun and the magnetic axis.

*Application of Mathematical Theory.*

6. Störmer's † calculations, founded on the radiation hypothesis, should give us some means of determining from theory the diurnal distribution of auroræ. The part of his researches which mostly interests us is the determination of the orbits through the origin ‡, and we shall mention a few of the results which have reference to our problem.

According to Störmer we get the various types of orbits through the origin (the centre of the earth) by the variation of a single integration constant $\gamma$. In order that rays starting from the origin shall pass on towards infinity $\gamma$ cannot be outside the interval (I)

$$-1<\gamma<0.$$

But values of $\gamma$ inside this interval may or may not give orbits through the origin with infinite branches.

Numerical integration has shown that all values of $\gamma$ in the interval ($I_1$)

$$-\gamma^*<\gamma<0,$$

give orbits through the origin which pass on towards infinity, $\gamma^*$ is found to be about 0·93. In the rest interval ($I_2$) $-1<\gamma<\gamma^*$ there are an infinite number of orbits which only reach a certain distance and then go back to the origin; but also in this interval an infinitely large number of orbits are found which have infinite branches.

If the rays from the sun reach the earth they must follow some path which is very near to one of those coming from the origin, and if the quantity $c=\sqrt{\frac{M}{H_0\rho_0}}$ § is less than the distance between the sun and the earth, the rays

† *Loc. cit.*

‡ See C. Störmer, *Archives des Sci. phys. et nat. Genève*, pp. 235–247 (1907).

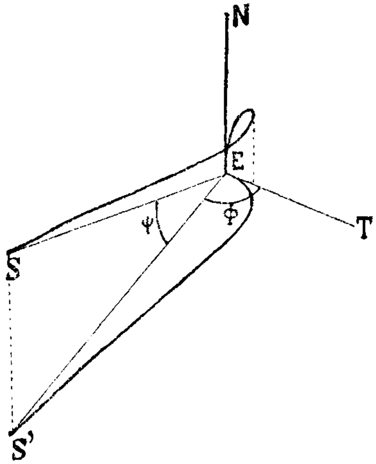
§ M is the magnetic moment of the earth, $\rho_0$ is the radius of curvature of the ray when moving in a uniform field of strength $H_0$ in a plane perpendicular to the magnetic force.

from the sun which are to reach the earth must follow near to orbits through the origin having infinite branches. The condition mentioned only requires $H_0\rho_0 \overline{\gtrless} 0{\cdot}38$, and the solar rays giving rise to the radiant forms here considered must undoubtedly fulfil this condition, on account of the fairly great penetrating power they possess; for it only means that the solar rays must be less deflectible than a cathode particle which has acquired its velocity from a potential fall of about 1/100 of a volt.

In order to get an idea of the diurnal distribution we may regard the distribution of precipitation of electric radiation, which at a certain moment would be produced by a rich supply of radiation from the sun

Suppose the rays to come from a point S whose distance from the point E corresponds to that between earth and sun. Let SE, fig. 5, form an angle $\psi$ with the plane perpendicular

Fig. 5.




to the magnetic axis. Suppose the orbit to be projected on this plane, and let the tangent (ET) of the projected orbit at the origin form an angle $\Phi$ with the line S′E. As shown by Störmer, $\Phi$ and $\psi$ are single-valued functions of $\gamma$; but we have to remember that $\Phi$ and $\psi$ only exist physically for intervals of $\gamma$ which give orbits through the origin with infinite branches.

Numerical integration has shown that the two functions $\Phi = f_1(\gamma)$ and $\psi = f_2(\gamma)$ are continuous and real in the interval $(I_1)$; in the interval $(I_2)$, however, if we only consider real values, the two functions $f_1(\gamma)$ and $f_2(\gamma)$ have a great number of points of discontinuity corresponding to orbits which do not pass on towards infinity, and the curves $f_1(\gamma)$ and $f_2(\gamma)$ break up into a number of separate parts. These curves have not yet been exactly determined; but from Störmer's investigations we see this much, that in the interval $(I_2)$ $\psi$ will oscillate inside a fairly small interval, while the angle $\Phi$, especially for orbits near those returning to the origin, may assume enormous values. In other words, the orbits of this interval may turn several times round the magnetic axis before they strike the earth.

As such a large variety of orbits corresponds to a very small interval of $\gamma$, very small variations in the initial conditions may cause great changes in the form and position of the auroræ. Consequently, we sh ouldexpect that auroræ, as far as they are produced by rays following orbits of the interval $(I_2)$, would on an average be spread over all hours of the day, and we should not expect auroræ formed in this way to produce very distinct maxima or minima. At the present stage of mathematical investigation we are not able either to prove the existence or to determine the position of such possible maxima corresponding to the interval $(I_2)$. For the auroræ possibly belonging to the interval $(I_1)$, however, we can estimate the position of the diurnal maxima.

A number of orbits of the interval $(I_1)$ are given in fig. 6, which is a photograph of a curve model made by Störmer. The orbits are all supposed to come from points situated in the same plane through the magnetic axis, and at a distance from the origin equal to that between earth and sun. Curve A, fig. 7, shows the relation between $\Phi$ and $\psi$ in this interval. When $\gamma$ passes from 0 to $-0{\cdot}93$ $\Phi$ increases from $0^\circ$ to $306^\circ$.

The position of the spot of precipitation is determined from theory by the position of the sun relative to the magnetic axis, and will be given by the points of intersection between the curve (A), fig. 7, and the straight line (B) given by the equation $\psi = +\delta_m$, where $90^\circ - \delta_m$ is the angle between the direction to the sun and the north direction of the magnetic axis.

The distribution previously found is derived from observations during the winter. In that case $\delta_m$ is negative, and the line B will intersect the curve A in four points, corresponding to four diurnal maxima. The first and the last one occur in the day and escape our observations. The points $m_1$ and $m_2$ are about symmetrically situated with respect to magnetic midnight and correspond to night maxima.

Thus the observations are so far in agreement with theory

Fig. 6.

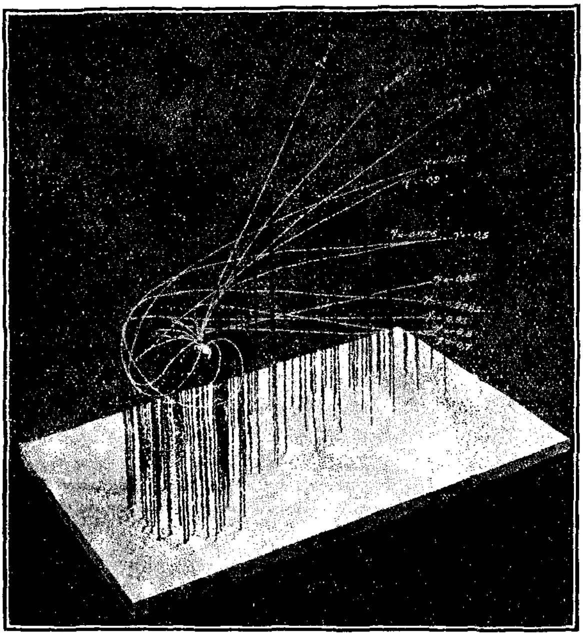
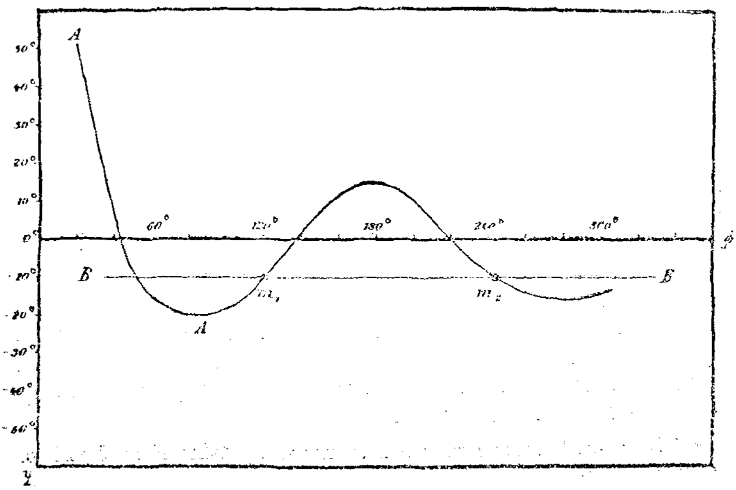


Fig. 7.



that the mere existence of two night maxima, one before and one after midnight, is a consequence of mathematical theory; but entering into details we should meet with many difficulties if we were to suppose that the predominant part of auroræ observed belonged to the interval ($I_1$).

Thus the two night maxima observed at the various stations are not symmetrical with respect to magnetic midnight, which should follow from theory provided the station was situated near the meridian passing through the magnetic axis (P′). Such a position has Kingua Fjord, but still the morning maximum occurs more than six hours after, while the evening maximum occurs only two hours before midnight.

Another difficulty arises from the fact that auroræ occur when $\delta_m$ has such large values that the line $\psi=\delta_m$ does not hit the curve A at all. Thus at Kingua Fjord the average value of $\delta_m$ at the time of the evening maximum is $24^\circ{\cdot}5$, and at midwinter even much greater, the largest (negative) value of $\psi$ in the interval ($I_1$) is no more than $20^\circ$.

Further, the diurnal maxima are not by any means so sharp as should be expected from theory, provided most auroræ were caused by the rays following orbits of the interval ($I_1$).

The broadening out of the maxima may have several causes. In the first place, auroræ are observed and may be counted even when they do not appear with their main bulk on the meridian of the place. Secondly, the curves are deduced from observations covering a period of several months, and during that time $\delta_m$ will undergo variations which will produce corresponding changes of $\Phi$ or the time of occurrence of the maxima. But these causes alone are not competent to explain the broadening of the maxima; for the same form may be observed near the zenith repeatedly for many hours during the very same evening; neither can it be due to differences of stiffness* of the solar rays, because, according to mathematical theory, when $\psi$ is the same, the *value of $\Phi$ is very little changed by considerable changes of stiffness.*

The discrepancies, however, may to a certain extent be ascribed to the incompleteness of the mathematical investigations, because the path of the rays near the earth may be greatly different from that of an elementary magnet, and near the poles a small difference of path may considerably alter the hour of occurrence.

* "Stiff rays" means rays which are not easily deflected by electric or magnetic forces.

The simplest way of explaining the indistinctness of the maxima is to suppose a great part of the auroræ to correspond to the interval ($I_2$). The great variety of forms of the orbits will also best account for the great variety of forms of auroral bands, and their rapid and often irregular motions.

7. Finally, we shall consider the question as to whether the distribution of auroræ is consistent with the assumption of a positive radiation.

Let, in fig. 5, the north pole be turned upwards, then the orbits drawn correspond to negative rays. The positive rays will have quite a similar course, only that they turn round the magnetic axis in the opposite direction, or orbits of positive rays are the mirror image of the negative ones with respect to a plane through the sun and the magnetic axis.

Now if the rays are negative the aurora occurring before magnetic midnight should correspond to $\Phi$ less than 180°. In accordance with the suggestion made by Birkeland I suggested, in a note to 'Nature'*, that the greater frequency of auroræ on the evening side compared with that on the morning side should indicate a negative radiation. This supposition is based on the assumption, which indeed might seem quite a reasonable one, that the simplest orbits, those corresponding to the interval $0 < \Phi < 180°$, should occur more frequently than orbits for which $\Phi$ is greater than 180°.

The mathematical theory, however, is not yet carried so far that the probability of the occurrence of various orbits has been found; but still the calculations made enable us to draw certain conclusions.

Looking at the curve A we notice that for values of $\Phi$ less than about 35°, $\psi$ is greater than any of the values $\delta_m$ can have, or radiation from the sun cannot at all follow those very simplest orbits passing from the earth towards infinity, because the sun cannot take up the position required.

Moreover, the results for Kingua Fjord are an exception to the rule that more auroræ occur round the evening than round the morning maximum. But even in the cases where the rule of the greater evening frequency holds, a negative charge of the rays is by no means a necessary consequence.

Provided the interval $I_2$ is excluded, $\Phi$ is found to be less than 360° and the value of $\Phi$ corresponding to the evening maximum is $180° \pm \alpha$, where $\alpha$ at the various stations has the fairly small values given in Table III., and the sign + corresponds to a positive, the sign − to a negative radiation.

The theory gave two night maxima about *symmetrically* situated with respect to magnetic midnight. Thus both

* *Loc. cit.*

$\Phi=180^\circ+\alpha$ and $180^\circ-\alpha$ may equally well correspond to a theoretical maximum; and thus, if we consider the auroræ regardless of their peculiar forms, the theory gives no reason for supposing orbits corresponding to $\Phi=180^\circ-\alpha$ more probable than orbits corresponding to $\Phi=180^\circ+\alpha$.

So far the theory of the diurnal distribution leaves the question with regard to the sign of the charge undecided.

If, however, we take into account the theoretical conditions for the formation of various forms, e. g. the draperies, we may get a step further.

Störmer, from his mathematical investigations, has succeeded in giving a fairly simple explanation of the formation of the thin and long drapery bands. Regarding details I must refer to his papers *. It may here be sufficient to notice that it is essential for his explanation that $\Phi$ has a great value, at least greater than 180°. If the rays correspond to the interval $(I_1)$ $\Phi$ must be in the interval $180^\circ<\Phi<360^\circ$, and if they follow some infinite orbit of the interval $(I_2)$, $\Phi$ might be even greater.

Thus, according to Störmer, the draperies, so far from being produced by the simplest orbits, are rather caused by rays following the more complicated ones, and *thus the reason for supposing that a negative radiation produces the draperies loses its foundation.*

In all cases investigated most drapery forms are found near the evening maximum: if so a positive radiation is the more likely; for, in the case of a positive radiation, the production of an evening maximum of drapery forms would only require $\Phi>180^\circ$, while in the case of a negative radiation it would require $\Phi>360^\circ$.

### *Explanation of Equidistant Bands.*

8. The explanation of a thin drapery band given by Störmer requires a radiation which is strictly homogeneous.

But, whatever the explanation may be with regard to details if we at all stick to the hypothesis that auroræ are formed by electric radiation from the sun, a homogeneous radiation will be necessary to account for the very sharp boundaries of extremely thin drapery bands; for a heterogeneous radiation composed of rays whose stiffness varies fairly continuously between wide limits will produce a broad and diffuse band. This follows from the law of motion of electric rays in the earth's magnetic field, because a variation of stiffness will correspond to a motion of the point where the ray strikes the

* *Arch. des Sciences,* &c. p. 336 (1907).

atmosphere taking place nearly perpendicular to the magnetic parallel along which the bands are usually directed. And if our interpretation of the structure is right, the sharp bottom edge of the drapery bands will require rays with the same penetrating power.

Now, on the other hand, we know that $\alpha$-rays given out from a radioactive compound during one single radioactive transformation are in fact homogeneous, and consequently *$\alpha$-rays from some radioactive compound are just the proper agency for the explanation of drapery bands.*

Another most characteristic and peculiar property of auroræ is the existence of equidistant bands (see fig. 2), and in order to explain their formation we shall merely have to suppose that each band corresponds to its own homogeneous radiation. In other words, *the radiation must be composed of a mixture of distinctly different homogeneous groups of rays*, and at the same time we must suppose that *these groups are all of them given out simultaneously from the same source on the sun and subject to the same initial conditions.*

These two conditions being present the mutual relation found between the bands will be easily understood. For the sake of simplicity we suppose only two groups to be present in the source.

Two rays, one of each group, leaving the source simultaneously along the same line, we shall call corresponding rays, and the points where they strike the atmosphere corresponding points.

Suppose now the conditions to be such that one of the groups gives rise to a band. If the difference of deflectibility is fairly small the second group will also strike the atmosphere. Now the difference of path of corresponding rays is entirely due to a different deflexion in the magnetic fields traversed, or to the difference of stiffness of the two groups which is a definite quantity, consequently the distance between corresponding points will vary continuously along the first band; and according to Störmer's calculations, when the band is extended nearly along the magnetic parallel, the corresponding points should keep their distance nearly unaltered all along the band, and each pair of corresponding points should be situated nearly on the same magnetic meridian. Thus the entire collection of corresponding points will form a band running nearly parallel to the first one.

Suppose the system to undergo a gradual change, which, *e. g.* may be due to a motion of the magnetic equator relative to the sun. Such a change may produce a motion of the bands; but if the two groups of rays are still sent out from the same source, the one band must at any moment be equidistant with the orher, it would appear as if the bands in a mysterious way were attached to each other. Indeed, such a motion is most characteristic, and often observed for a system of parallel auroral bands.

If we did not know the radioactive processes, it would indeed seem a rather artificial explanation, which was built on the assumption of a mixture of homogeneous rays given out from the same source; for any kind of electric discharge producing such conditions is almost inconceivable. On the other hand, when we assume a kind of $\alpha$-radiation to produce the bands such conditions are not only conceivable, but may rather be considered a necessary consequence, because a number of radioactive compounds intimately mixed, each producing its own homogeneous $\alpha$-radiation, will be formed by atomic disintegration of some parent substance.

In this connexion it may be well to remember that any homogeneous radiation would have to start from the sun in such a way that the rays were able to pass into space without traversing any appreciable layers of matter, and if radioactive substances formed the source, they would have to exist in very thin layers. A radioactive emanation ejected from the sun and disintegrating would fulfil all necessary conditions.

From our point of view the drapery bands should give a kind of *magnetic spectrum* of the homogeneous groups of $\alpha$-rays present in the source, and as the $\alpha$-rays are characteristic of the substances emitting them, a possibility opens out of studying or identifying the family of radioactive substances present in the sun by observing the relative distances between the various bands.

If we adopt the simplified system of an elementary magnet we may, from a formula given by Störmer, calculate the position of the bands caused by $\alpha$-rays from a certain family of radioactive substances.

Let $\omega$ denote the angle between the magnetic axis and a line from the earth's centre to the band, and let D be the distance from the centre of the earth to the bottom edge of the band, then

$$\sin\omega = \sqrt{2\gamma_1 \frac{D}{c}}, \text{ where } c = \sqrt{\frac{M}{H_0\rho_0}}.$$

For the draperies to be formed $\gamma_1$ must be between 0·9 and 1. A change of $\omega$ corresponding to a change of deflectibility is found from the relation

$$\Delta\omega = -\tfrac{1}{2}\tan\omega\,\frac{\Delta c}{c}.$$

For $\alpha$-rays from radium emanation we find $\omega = 16^\circ\cdot 5$. *This result is a most important one when taken in connexion with the position of the auroral zone.* According to the chart given by Fritz, the auroral zone for equal frequency on the northern and southern sky is situated at an angular distance from the magnetic axis of about 17° or 18°, consequently *$\alpha$-rays of the ordinary kind have just the proper stiffness to give the right position of the auroral zone.*

The relative position of the bands corresponding to $\alpha$-rays from the radium family is given in the following table :—

TABLE IV.

| Substance. | Distance from Ra band. | Distance between successive bands. | Apparent angle between succes. bands. |
|---|---|---|---|
| Ra ......... | 0 km. | | |
| | | 24 km. | 11°·5 |
| Pol. ......... | 24 ,, | | |
| | | 15 ,, | 7°·2 |
| Ra Em. ... | 39 ,, | | |
| | | 25 ,, | 11°·9 |
| Ra A ...... | 64 ,, | | |
| | | 69 ,, | 33° |
| Ra C ...... | 133 ,, | | |

The bands are supposed to be seen near the zenith at a height of 120 km.

The material at my disposal gives no means of any exact comparison with observations. Such comparison, however, may be possible by the development of the photographic method. But this much can already be said, that the values found are of the right order, or, differences of stiffness as those of $\alpha$-rays from ordinary radioactive substances are competent to explain the distances between successive bands actually observed.

## *The Light of Aurora.*

The various lines in the auroral spectrum have not yet been interpreted with any certainty by means of spectra physically known. The greater number of lines have probably rightly been identified with lines of the spectrum of air and some of the rare gases ; but the origin of the most conspicuous line with the wave-length $\lambda = 5570$ is still unknown.

As early as 1874 Ångström * came to the conclusion

* Ångström, Pogg. *Ann. Jubelbd.* p. 424 (1874).

that the line 5570 was due to fluorescent or phosphorescent light. Later on, A. Schuster * called attention to the fact that this auroral line very nearly coincides with one of the krypton lines ($\lambda = 5570{\cdot}4$). According to Kayser, however, this coincidence does not prove identity of the two lines; for the auroral spectrum does not give the other krypton lines with the intensity to be expected from the ordinary krypton spectra.

The difficulty in interpreting the auroral spectrum indicates that the spectrum depends essentially on the peculiar way in which it is produced.

According to the view put forward in this paper, the light is produced by an electric radiation of the $\alpha$-ray type penetrating down the upper strata of the atmosphere. At present we do not know very much with regard to the nature of the light produced in this way.

The spontaneous luminosity given out from $RaBr_2$ has been examined by Sir William and Lady Huggins †. They found the part of the spectrum examined to be essentially similar to the *negative* band spectrum of nitrogen, and besides they found a band (about $\lambda = 5165$) the origin of which they were unable to explain. From the fatigue effect produced by hydrogen they concluded that the $\beta$-rays did not greatly contribute to the luminosity, which they supposed to be given out from the region inside the solid substance.

B. Walter ‡ was the first to show that light was also given out from the air surrounding the radioactive substance. He experimented on polonium and found a spectrum similar to that of radium bromide; but in the case of polonium it more resembled the *positive* band spectrum of nitrogen.

R. Pohl §, F. Himstedt and G. Meyer ‖, showed that, also in the case of radium bromide, the surrounding air gave out a faint luminosity which could be detected photographically. R. Pohl states that luminosity in the air can be observed several centimetres from the substance.

As polonium only gives out $\alpha$-rays and the very absorbable $\delta$-rays which do not ionize, the luminosity given out from the air several centimetres from the substance must be produced by $\alpha$-rays.

When we are going to make comparison with the auroral

* A. Schuster, 'Nature,' No. 58, p. 151 (1898).

† Sir William and Lady Huggins, Proc. Roy. Soc. lxxii. pp. 196 and 409 (1903); lxxvi. p. 488 (1905).

‡ B. Walter, *Ann. d. Physik,* xvii. p. 367 (1905); xx. p. 327 (1906).

§ R. Pohl, *Verh. d. D. Phys. Ges.* vii. p. 458 (1906).

‖ F. Himstedt and G. Meyer, *Ber. d. naturf. Ges. zu Freiburg in Br.* xvi. p. 13 (1905).

spectrum, however, we must remember that the auroræ are produced under circumstances very different from those present in the previous experiments. Thus the solar rays have a much greater density and penetrate through rarified gases and perhaps also fine dust particles, and these differences might account for the greater number of lines observed in the auroral spectrum and the appearance of the auroral line $\lambda = 5570$.

The spectrum of the phosphorescent light produced by $\alpha$-rays falling on certain substances has been examined by E. Marsden *. Zinc sulphide gave a single band extending from $\lambda = 5920$ to $\lambda = 4250$, and willemite a band between $\lambda = 5800$ and $\lambda = 4870$. The auroral line falls in the middle of these bands.

The spectral analysis at its present state may indeed furnish us with certain suggestive points; but it does not give an *experimentum crucis* for the determination of the nature of those rays which produce aurora borealis. We shall have to wait for further experiments; but already the previous experiments have shown that $\alpha$-rays (compared with the other radium rays) are very effective in producing luminosity in the air through which they pass, a property which is very essential if rays of this type are to explain the brilliancy of auroræ.

Rays consisting of atoms or molecules might not only make the matter through which they pass luminous, but by their impact they might themselves give out light. If so, we should have a means of investigating the nature of the carrier by observing the Doppler effect in the auroral spectrum of those lines which are produced by the radiation itself.

The spectrum analysis of the light produced by $\alpha$-rays, however, gave no trace of helium lines. Thus in this case the light given out from the carrier is either wanting or very feeble as compared with that produced in the surrounding air.

The difficulty in detecting a possible spectrum from the carrier is made even greater through the Doppler effect, which for the very large velocities would amount to about one-tenth of the total wave-length. The light from the auroræ entering the spectroscope will usually correspond to directions forming the most different angles with the direction of the radiation; consequently the light corresponding to a certain line from the carrier would be spread out to a

* E. Marsden, Proc. Roy. Soc. A. lxxxiii. p. 548 (1910).

fairly broad band, which in the green spectrum may cover as much as 500 Å.

The definite sharp lines observed in the auroral spectrum are therefore no doubt due to light produced in the atmosphere, and do not originate from the radiation itself.

### *Concluding Remarks.*

From the study of the structure of the radiant forms of aurora, we found that the rays producing them had a number of characteristic properties in common with $\alpha$-rays.

The investigation with regard to diurnal distribution showed that, so far as our present knowledge goes, the assumption of a positive charge is not only a legitimate one, but is even the most favourable for the explanation of the occurrence of drapery forms.

From the point of view of the radiation hypothesis the extremely thin drapery bands have to be produced by a strictly homogeneous radiation, and the parallel bands were explained in a simple way by assuming groups of homogeneous rays to emanate from the same source. This explanation gave a strong argument in favour of the view that the solar rays are not merely of the $\alpha$-ray type, but are indeed *$\alpha$-rays of some sort given out from radioactive substances.*

With regard to the position of auroræ, we found that the stiffness of ordinary $\alpha$-rays gave the right distance from the magnetic axis, and their penetrating power was sufficient to account for the altitude of a great part of the auroræ observed.

Thus, as far as our investigations have been carried, the ordinary $\alpha$-rays are found to possess the right charge, scattering, stiffness, and penetrating power, which are necessary to explain most characteristic properties of a great number of auroræ.

But still we ought to be aware of the possibility that not all auroral forms are necessarily produced in the same way and by the same radiation. It is quite possible that auroræ in certain cases may partly be secondary effects of precipitations of solar rays, and that certain diffuse forms may be produced by corpuscular rays. And even in the case of the radiant forms with straight-lined structure, it is still a matter for further investigation to determine in each case the atoms or molecules which form the carriers of the electric rays.

Provided relation (2) holds good for all possible velocities, we found that an ordinary $\alpha$-particle, even with the velocity of light, could not reach within a distance of 27 km. from the ground. On the other hand, many observers have found auroræ, especially rays and ray-bundles, to reach within a distance of one km. If so, the rays must possess an enormous penetrating power, and yet the straight-lined structure will make a radiation of the $\alpha$-ray type necessary; but it is a type not yet known from laboratory experiments.

It is a remarkable fact that the rays and ray-bundles often shoot down in between other forms of aurora which do not reach so near to the earth. In view of our radiation hypothesis, this would mean that these very penetrating rays had about the same stiffness as ordinary $\alpha$-rays, or

$$\frac{mv}{ne} = \frac{m_0 v_0}{2e} \text{ (approximately)},$$

where $m$ and $v$ are respectively the mass and velocity of the solar rays and $ne$ the charge of each particle; $m_0$, $v_0$, and $2e$ are the corresponding quantities for $\alpha$-rays.

From what we know about the charge carried by the small ions and by the positive rays in vacuum-tubes, $n$ ought to be a very small number. Then in order to explain the great penetrating power of the solar rays, we should have to suppose a carrier smaller than a helium atom, but moving with a velocity so much greater than that of $\alpha$-rays that the above relation is fulfilled. The carrier might either be hydrogen or some gas lighter than hydrogen, and the possibility suggests itself that coronium may form the carrier of the most penetrating solar rays.

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## XIX. *Note on the Cosine Law of Radiation.* *By* Louis Vessot King, *B.A.* (*Cantab.*), *Lecturer in Physics, McGill University* *.

§ 1. It is a well-established fact in the theory of light that the intensity in a parallel beam of homogeneous radiation travelling a distance $x$ through an absorbing medium is diminished according to the exponential law

$$I = I_0 e^{-\kappa x}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $I_0$ is the intensity over unit cross-section measured at an arbitrary origin $x = 0$. $\kappa$ is a constant for the medium, called the *coefficient of absorption*, and depends on the wave-length of the radiation.

If the radiation emanate from a point-source $s$, we consider

* Communicated by Prof. H. T. Barnes, F.R.S.