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A POPULAR HISTORY OF ASTRONOMY

DURING THE NINETEENTH CENTURY

BY THE SAME AUTHOR

THE GREAT NEBULA IN ORION, 1883

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See p. 408

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THE NINETEENTH CENTURY

BY

AGNES M. CLERKE

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PREFACE TO THE FOURTH EDITION

Since the third edition of the present work issued from the press, the nineteenth century has run its course and finished its record. A new era has dawned, not by chronological prescription alone, but to the vital sense of humanity. Novel thoughts are rife; fresh impulses stir the nations; the soughing of the wind of progress strikes every ear. “The old order changeth” more and more swiftly as mental activity becomes intensified. Already many of the scientific doctrines implicitly accepted fifteen years ago begin to wear a superannuated aspect. Dalton’s atoms are in process of disintegration; Kirchhoff’s theorem visibly needs to be modified; Clerk Maxwell’s medium no longer figures as an indispensable factotum; “absolute zero” is known to be situated on an asymptote to the curve of cold. Ideas, in short, have all at once become plastic, and none more completely so than those relating to astronomy. The physics of the heavenly bodies, indeed, finds its best opportunities in unlooked-for disclosures; for it deals with transcendental conditions, and what is strange to terrestrial experience may serve admirably to expound what is normal in the skies. In celestial science especially, facts that appear subversive are often the most illuminative, and the prospect of its advance widens and brightens with each divagation enforced or permitted from the strait paths of rigid theory.

This readiness for innovation has undoubtedly its dangers and drawbacks. To the historian, above all, it presents frequent occasions of embarrassment. The writing of history is a strongly selective operation, the outcome being valuable just in so far as the choice what to reject and what to include has been judicious; and the task is no light one of discriminating between barren speculations and ideas pregnant with coming truth. To the possession of such prescience of the future as would be needed to do this effectually I can lay no claim; but diligence and sobriety of thought are ordinarily within reach, and these I shall have exercised to good purpose if I have succeeded in rendering the fourth edition of *A Popular History of Astronomy during the Nineteenth Century* not wholly unworthy of a place in the scientific literature of the twentieth century.

My thanks are due to Sir David Gill for the use of his photograph of the great comet of 1901, which I have added to my list of illustrations, and to the Council of the Royal Astronomical Society for the loan of glass positives needed for the reproduction of those included in the third edition.

London, *July*, 1902.

PREFACE TO THE FIRST EDITION

The progress of astronomy during the last hundred years has been rapid and extraordinary. In its distinctive features, moreover, the nature of that progress has been such as to lend itself with facility to untechnical treatment. To this circumstance the present volume owes its origin. It embodies an attempt to enable the ordinary reader to follow, with intelligent interest, the course of modern astronomical inquiries, and to realize (so far as it can at present be realized) the full effect of the comprehensive change in the whole aspect, purposes, and methods of celestial science introduced by the momentous discovery of spectrum analysis.

Since Professor Grant's invaluable work on the *History of Physical Astronomy* was published, a third of a century has elapsed. During the interval a so-called "new astronomy" has grown up by the side of the old. One effect of its advent has been to render the science of the heavenly bodies more popular, both in its needs and in its nature, than formerly. More popular in its needs, since its progress now primarily depends upon the interest in, and consequent efforts towards its advancement of the general public; more popular in its nature, because the kind of knowledge it now chiefly tends to accumulate is more easily intelligible—less remote from ordinary experience—than that evolved by the aid of the calculus from materials collected by the use of the transit-instrument and chronograph.

It has thus become practicable to describe in simple language the most essential parts of recent astronomical discoveries, and, being practicable, it could not be otherwise than desirable to do so. The service to astronomy itself would be not inconsiderable of enlisting wider sympathies on its behalf, while to help one single mind towards a fuller understanding of the manifold works which have in all ages irresistibly spoken to man of the glory of God might well be an object of no ignoble ambition.

The present volume does not profess to be a complete or exhaustive history of astronomy during the period covered by it. Its design is to present a view of the progress of celestial science, on its most characteristic side, since the time of Herschel. Abstruse mathematical theories, unless in some of their more striking results, are excluded from consideration. These, during the eighteenth century, constituted the sum and substance of astronomy, and their fundamental importance can never be diminished, and should never be ignored. But as the outcome of the enormous development given to the powers of the telescope in recent times, together with the swift advance of physical science, and the inclusion, by means of the spectroscope, of the heavenly bodies within the domain of its inquiries, much knowledge has been acquired regarding the nature and condition of those bodies, forming, it might be said, a science apart, and disembarrassed from immediate dependence upon intricate, and, except to the initiated, unintelligible formulæ. This kind of knowledge forms the main subject of the book now offered to the public.

There are many reasons for preferring a history to a formal treatise on astronomy. In a treatise, *what* we know is set forth. A history tells us, in addition, *how* we came to know it. It thus places facts before us in the natural order of their ascertainment, and narrates instead of enumerating. The story to be told leaves the marvels of imagination far behind, and requires no embellishment from literary art or high-flown phrases. Its best ornament is unvarnished truthfulness, and this, at least, may confidently be claimed to be bestowed upon it in the ensuing pages.

In them unity of treatment is sought to be combined with a due regard to chronological sequence by grouping in separate chapters the various events relating to the several departments of descriptive astronomy. The whole is divided into two parts, the line between which is roughly drawn at the middle of the present century. Herschel’s inquiries into the construction of the heavens strike the keynote of the first part; the discoveries of sun-spot and magnetic periodicity and of spectrum analysis determine the character of the second. Where the nature of the subject required it, however, this arrangement has been disregarded. Clearness and consistency should obviously take precedence of method. Thus, in treating of the telescopic scrutiny of the various planets, the whole of the related facts have been collected into an uninterrupted narrative. A division elsewhere natural and helpful would here have been purely artificial, and therefore confusing.

The interests of students have been consulted by a full and authentic system of references to the sources of information relied upon. Materials have been derived, as a rule with very few exceptions, from the original authorities. The system adopted has been to take as little as possible at second-hand. Much pains have been taken to trace the origin of ideas, often obscurely enunciated long before they came to resound through the scientific world, and to give to each individual discoverer, strictly and impartially, his due. Prominence has also been assigned to the biographical element, as underlying and determining the whole course of human endeavour. The advance of knowledge may be called a vital process. The lives of men are absorbed into and assimilated by it. Inquiries into the kind and mode of the surrender in each separate case must always possess a strong interest, whether for study or for example.

The acknowledgments of the writer are due to Professor Edward S. Holden, director of the Washburn Observatory, Wisconsin, and to Dr. Copeland, chief astronomer of Lord Crawford's Observatory at Dunecht, for many valuable communications.

London, *September*, 1885.

CONTENTS

CHAPTER XII

STARS AND NEBULÆ

CHAPTER XIII

METHODS OF RESEARCH

APPENDIX

INDEX

LIST OF ILLUSTRATIONS

HISTORY OF ASTRONOMY

DURING THE NINETEENTH CENTURY

INTRODUCTION

We can distinguish three kinds of astronomy, each with a different origin and history, but all mutually dependent, and composing, in their fundamental unity, one science. First in order of time came the art of observing the returns, and measuring the places, of the heavenly bodies. This was the sole astronomy of the Chinese and Chaldeans; but to it the vigorous Greek mind added a highly complex geometrical plan of their movements, for which Copernicus substituted a more harmonious system, without as yet any idea of a compelling cause. The planets revolved in circles because it was their nature to do so, just as laudanum sets to sleep because it possesses a *virtus dormitiva*. This first and oldest branch is known as "observational," or "practical astronomy." Its business is to note facts as accurately as possible; and it is essentially unconcerned with schemes for connecting those facts in a manner satisfactory to the reason.

The second kind of astronomy was founded by Newton. Its nature is best indicated by the term "gravitational"; but it is also called "theoretical astronomy."[1] It is based on the idea of cause; and the whole of its elaborate structure is reared according to the dictates of a single law, simple in itself, but the tangled web of whose consequences can be unravelled only by the subtle agency of an elaborate calculus.

The third and last division of celestial science may properly be termed "physical and descriptive astronomy." It seeks to know what the heavenly bodies are in themselves, leaving the How? and the Wherefore? of their movements to be otherwise answered. Now, such inquiries became possible only through the invention of the telescope, so that Galileo was, in point of fact, their originator. But Herschel first gave them a prominence which the whole progress of science during the nineteenth century served to confirm and render more exclusive. Inquisitions begun with the telescope have been extended and made effective in unhoped-for directions by the aid of the spectroscope and photographic camera; and a large part of our attention in the present volume will be occupied with the brilliant results thus achieved.

The unexpected development of this new physical-celestial science is the leading fact in recent astronomical history. It was out of the regular course of events. In the degree in which it has actually occurred it could certainly not have been foreseen. It was a seizing of the prize by a competitor who had hardly been thought qualified to enter the lists. Orthodox astronomers of the old school looked with a certain contempt upon observers who spent their nights in scrutinising the faces of the moon and planets rather than in timing their transits, or devoted daylight energies, not to reductions and computations, but to counting and measuring spots on the sun. They were regarded as irregular practitioners, to be tolerated perhaps, but certainly not encouraged.

The advance of astronomy in the eighteenth century ran in general an even and logical course. The age succeeding Newton's had for its special task to demonstrate the universal validity, and trace the complex results, of the law of gravitation. The accomplishment of that task occupied just one hundred years. It was virtually brought to a close when Laplace explained to the French Academy, November 19, 1787, the cause of the moon's accelerated motion. As a mere machine, the solar system, so far as it was then known, was found to be complete and intelligible in all its parts; and in the *Mécanique Céleste* its mechanical perfections were displayed under a form of majestic unity which fitly commemorated the successive triumphs of analytical genius over problems amongst the most arduous ever dealt with by the mind of man.

Theory, however, demands a practical test. All its data are derived from observation; and their insecurity becomes less tolerable as it advances nearer to perfection. Observation, on the other hand, is the pitiless critic of theory; it detects weak points, and provokes reforms which may be the beginnings of discovery. Thus, theory and observation mutually act and react, each alternately taking the lead in the endless race of improvement.

Now, while in France Lagrange and Laplace were bringing the gravitational theory of the solar system to completion, work of a very different kind, yet not less indispensable to the future welfare of astronomy, was being done in England. The Royal Observatory at Greenwich is one of the few useful institutions which date their origin from the reign of Charles II. The leading position which it still occupies in the science of celestial observation was, for near a century and a half after its foundation, an exclusive one. Delambre remarked that, had all other materials of the kind been destroyed, the Greenwich records alone would suffice for the restoration of astronomy. The establishment was indeed absolutely without a rival.[2] Systematic observations of sun, moon, stars, and planets were during the whole of the eighteenth century made only at Greenwich. Here materials were accumulated for the secure correction of theory, and here refinements were introduced by which the exquisite accuracy of modern practice in astronomy was eventually attained.

The chief promoter of these improvements was James Bradley. Few men have possessed in an equal degree with him the power of seeing accurately, and reasoning on what they see. He let nothing pass. The slightest inconsistency between what appeared and what was to be expected roused his keenest attention; and he never relaxed his mental grip of a subject until it had yielded to his persistent inquisition. It was to these qualities that he owed his discoveries of the aberration of light and the nutation of the earth's axis. The first was announced in 1729. What is meant by it is that, owing to the circumstance of light not being instantaneously transmitted, the heavenly bodies appear shifted from their true places by an amount depending upon the ratio which the velocity of light bears to the speed of the earth in its orbit. Because light travels with enormous rapidity, the shifting is very slight; and each star returns to its original position at the end of a year.

Bradley's second great discovery was finally ascertained in 1748. Nutation is a real "nodding" of the terrestrial axis produced by the dragging of the moon at the terrestrial equatorial protuberance. From it results an *apparent* displacement of the stars, each of them describing a little ellipse about its true or "mean" position, in a period of nearly nineteen years.

Now, an acquaintance with the fact and the laws of each of these minute irregularities is vital to the progress of observational astronomy; for without it the places of the heavenly bodies could never be accurately known or compared. So that Bradley, by their detection, at once raised the science to a higher grade of precision. Nor was this the whole of his work. Appointed Astronomer-Royal in 1742, he executed during the years 1750-62 a series of observations which formed the real beginning of exact astronomy. Part of their superiority must, indeed, be attributed to the co-operation of John Bird, who provided Bradley in 1750 with a measuring instrument of till then unequalled excellence. For not only was the art of observing in the eighteenth century a peculiarly English art, but the means of observing were furnished almost exclusively by British artists. John Dollond, the son of a Spitalfields weaver, invented the achromatic lens in 1758, removing thereby the chief obstacle to the development of the powers of refracting telescopes; James Short, of Edinburgh, was without a rival in the construction of reflectors; the sectors, quadrants, and circles of Graham, Bird, Ramsden, and Cary were inimitable by Continental workmanship.

Thus practical and theoretical astronomy advanced on parallel lines in England and France respectively, the improvement of their several tools—the telescope and the quadrant on the one side, and the calculus on the other—keeping pace. The whole future of the science seemed to be theirs. The cessation of interest through a too speedy attainment of the perfection towards which each spurred the other, appeared to be the only danger it held in store for them. When all at once, a rival stood by their side—not, indeed, menacing their progress, but threatening to absorb their popularity.

The rise of Herschel was the one conspicuous anomaly in the astronomical history of the eighteenth century. It proved decisive of the course of events in the nineteenth. It was unexplained by anything that had gone before; yet all that came after hinged upon it. It gave a new direction to effort; it lent a fresh impulse to thought. It opened a channel for the widespread public interest which was gathering towards astronomical subjects to flow in.

Much of this interest was due to the occurrence of events calculated to arrest the attention and excite the wonder of the uninitiated. The predicted return of Halley's comet in 1759 verified, after an unprecedented fashion, the computations of astronomers. It deprived such bodies for ever of their portentous character; it ranked them as denizens of the solar system. Again, the transits of Venus in 1761 and 1769 were the first occurrences of the kind since the awakening of science to their consequence. Imposing preparations, journeys to remote and hardly accessible regions, official expeditions, international communications, all for the purpose of observing them to the best advantage, brought their high significance vividly to the public consciousness; a result aided by the facile pen of Lalande, in rendering intelligible the means by which these elaborate arrangements were to issue in an accurate knowledge of the sun's distance. Lastly, Herschel's discovery of Uranus, March 13, 1781, had the surprising effect of utter novelty. Since the human race had become acquainted with the company of the planets, no addition had been made to their number. The event thus broke with immemorial traditions, and seemed to show astronomy as still young and full of unlooked-for possibilities.

Further popularity accrued to the science from the sequel of a career so strikingly opened. Herschel's huge telescopes, his detection by their means of two Saturnian and as many Uranian moons, his piercing scrutiny of the sun, picturesque theory of its constitution, and sagacious indication of the route pursued by it through space; his discovery of stellar revolving systems, his bold soundings of the universe, his grandiose ideas, and the elevated yet simple language in which they were conveyed—formed a combination powerfully effective to those least susceptible of new impressions. Nor was the evoked enthusiasm limited to the British Isles. In Germany, Schröter followed—*longo intervallo*—in Herschel's track. Von Zach set on foot from Gotha that general communication of ideas which gives life to a forward movement. Bode wrote much and well for unlearned readers. Lalande, by his popular lectures and treatises, helped to form an audience which Laplace himself did not disdain to address in the *Exposition du Système du Monde*.

This great accession of public interest gave the impulse to the extraordinarily rapid progress of astronomy in the nineteenth century. Official patronage combined with individual zeal sufficed for the elder branches of the science. A few well-endowed institutions could accumulate the materials needed by a few isolated thinkers for the construction of theories of wonderful beauty and elaboration, yet precluded, by their abstract nature, from winning general applause. But the new physical astronomy depends for its prosperity upon the favour of the multitude whom its striking results are well fitted to attract. It is, in a special manner, the science of amateurs. It welcomes the most unpretending co-operation. There is no one "with a true eye and a faithful hand" but can do good work in watching the heavens. And not unfrequently, prizes of discovery which the most perfect appliances failed to grasp, have fallen to the share of ignorant or ill-provided assiduity.

Observers, accordingly, have multiplied; observatories have been founded in all parts of the world; associations have been constituted for mutual help and counsel. A formal astronomical congress met in 1789 at Gotha—then, under Duke Ernest II. and Von Zach, the focus of German astronomy—and instituted a combined search for the planet suspected to revolve undiscovered between the orbits of Mars and Jupiter. The Astronomical Society of London was established in 1820, and the similar German institution in 1863. Both have been highly influential in promoting the interests, local and general, of the science they are devoted to forward; while functions corresponding to theirs have been discharged elsewhere by older or less specially constituted bodies, and new ones of a more popular character are springing up on all sides.

Modern facilities of communication have helped to impress more deeply upon modern astronomy its associative character. The electric telegraph gives a certain ubiquity which is invaluable to an observer of the skies. With the help of a wire, a battery, and a code of signals, he sees whatever is visible from any portion of our globe, depending, however, upon other eyes than his own, and so entering as a unit into a widespread organisation of intelligence. The press, again, has been a potent agent of co-operation. It has mainly contributed to unite astronomers all over the world into a body animated by the single aim of collecting “particulars” in their special branch for what Bacon termed a History of Nature, eventually to be interpreted according to the sagacious insight of some one among them gifted above his fellows. The first really effective astronomical periodical was the *Monatliche Correspondenz,* started by Von Zach in the year 1800. It was followed in 1822 by the *Astronomische Nachrichten*, later by the *Memoirs* and *Monthly Notices* of the Astronomical Society, and by the host of varied publications which now, in every civilised country, communicate the discoveries made in astronomy to divers classes of readers, and so incalculably quicken the current of its onward flow.

Public favour brings in its train material resources. It is represented by individual enterprise, and finds expression in an ample liberality. The first regular observatory in the Southern Hemisphere was founded at Paramatta by Sir Thomas Makdougall Brisbane in 1821. The Royal Observatory at the Cape of Good Hope was completed in 1829. Similar establishments were set to work by the East India Company at Madras, Bombay, and St. Helena, during the first third of the nineteenth century. The organisation of astronomy in the United States of America was due to a strong wave of popular enthusiasm. In 1825 John Quincy Adams vainly urged upon Congress the foundation of a National Observatory; but in 1843 the lectures on celestial phenomena of Ormsby MacKnight Mitchel stirred an impressionable audience to the pitch of providing him with the means of erecting at Cincinnati the first astronomical establishment worthy the name in that great country. On the 1st of January, 1882, no less than one hundred and forty-four were active within its boundaries.

The apparition of the great comet of 1843 gave an additional fillip to the movement. To the excitement caused by it the Harvard College Observatory—called the “American Pulkowa”—directly owed its origin; and the example was not ineffective elsewhere. The United States Naval Observatory was built in 1844, Lieutenant Maury being its first Director. Corporations, universities, municipalities, vied with each other in the creation of such institutions; private subscriptions poured in; emissaries were sent to Europe to purchase instruments and to procure instruction in their use. In a few years the young Republic was, in point of astronomical efficiency, at least on a level with countries where the science had been fostered since the dawn of civilisation.

A vast widening of the scope of astronomy has accompanied, and in part occasioned, the great extension of its area of cultivation which our age has witnessed. In the last century its purview was a comparatively narrow one. Problems lying beyond the range of the solar system were almost unheeded, because they seemed inscrutable. Herschel first showed the sidereal universe as accessible to investigation, and thereby offered to science new worlds—majestic, manifold, “infinitely infinite” to our apprehension in number, variety, and extent—for future conquest. Their gradual appropriation has absorbed, and will long continue to absorb, the powers which it has served to develop.

But this is not the only direction in which astronomy has enlarged, or rather has levelled, its boundaries. The unification of the physical sciences is perhaps the greatest intellectual feat of recent times. The process has included astronomy; so that, like Bacon, she may now be said to have “taken all knowledge” (of that kind) “for her province.” In return, she proffers potent aid for its increase. Every comet that approaches the sun is the scene of experiments in the electrical illumination of rarefied matter, performed on a huge scale for our benefit. The sun, stars, and nebulæ form so many celestial laboratories, where the nature and mutual relations of the chemical “elements” may be tried by more stringent tests than sublunary conditions afford. The laws of terrestrial magnetism can be completely investigated only with the aid of a concurrent study of the face of the sun. The solar spectrum will perhaps one day, by its recurrent modifications, tell us something of impending droughts, famines, and cyclones.

Astronomy generalises the results of the other sciences. She exhibits the laws of Nature working over a wider area, and under more varied conditions, than ordinary experience presents. Ordinary experience, on the other hand, has become indispensable to her progress. She takes in at one view the indefinitely great and the indefinitely little. The mutual revolutions of the stellar multitude during tracts of time which seem to lengthen out to eternity as the mind attempts to traverse them, she does not admit to be beyond her ken; nor is she indifferent to the constitution of the minutest atom of matter that thrills the ether into light. How she entered upon this vastly expanded inheritance, and how, so far, she has dealt with it, is attempted to be set forth in the ensuing chapters.

FOOTNOTES:

[1] The denomination "physical astronomy," first used by Kepler, and long appropriated to this branch of the science, has of late been otherwise applied.

[2] *Histoire de l'Astronomie au xviiie Siècle*, p. 267.

PART I

PROGRESS OF ASTRONOMY DURING THE FIRST HALF OF THE NINETEENTH CENTURY

CHAPTER I

FOUNDATION OF SIDEREAL ASTRONOMY

Until nearly a hundred years ago the stars were regarded by practical astronomers mainly as a number of convenient fixed points by which the motions of the various members of the solar system could be determined and compared. Their recognised function, in fact, was that of milestones on the great celestial highway traversed by the planets, as well as on the byways of space occasionally pursued by comets. Not that curiosity as to their nature, and even conjecture as to their origin, were at any period absent. Both were from time to time powerfully stimulated by the appearance of startling novelties in a region described by philosophers as “incorruptible,” or exempt from change. The catalogue of Hipparchus probably, and certainly that of Tycho Brahe, some seventeen centuries later, owed each its origin to the temporary blaze of a new star. The general aspect of the skies was thus (however imperfectly) recorded from age to age, and with improved appliances the enumeration was rendered more and more accurate and complete; but the secrets of the stellar sphere remained inviolate.

In a qualified though very real sense, Sir William Herschel may be called the Founder of Sidereal Astronomy. Before his time some curious facts had been noted, and some ingenious speculations hazarded, regarding the condition of the stars, but not even the rudiments of systematic knowledge had been acquired. The facts ascertained can be summed up in a very few sentences.

Giordano Bruno was the first to set the suns of space in motion; but in imagination only. His daring surmise was, however, confirmed in 1718, when Halley announced[3] that Sirius, Aldebaran, Betelgeux, and Arcturus had unmistakably shifted their quarters in the sky since Ptolemy assigned their places in his catalogue. A similar conclusion was reached by J. Cassini in 1738, from a comparison of his own observations with those made at Cayenne by Richer in 1672; and Tobias Mayer drew up in 1756 a list showing the direction and amount of about fifty-seven proper motions,[4] founded on star-places determined by Olaus Römer fifty years previously. Thus the stars were no longer regarded as “fixed,” but the question remained whether the movements perceived were real or only apparent; and this it was not yet found possible to answer. Already, in the previous century, the ingenious Robert Hooke had suggested an “alteration of the very system of the sun,”[5] to account for certain suspected changes in stellar positions; Bradley in 1748, and Lambert in 1761, pointed out that such apparent displacements (by that time well ascertained) were in all probability a combined effect of motions both of sun and stars; and Mayer actually attempted the analysis, but without result.

On the 13th of August, 1596, David Fabricius, an unprofessional astronomer in East Friesland, saw in the neck of the Whale a star of the third magnitude, which by October had disappeared. It was, nevertheless, visible in 1603, when Bayer marked it in his catalogue with the Greek letter o, and was watched, in 1638-39, through its phases of brightening and apparent extinction by a Dutch professor named Holwarda.[6] From Hevelius this first-known periodical star received the name of "Mira," or the Wonderful, and Boulliaud in 1667 fixed the length of its cycle of change at 334 days. It was not a solitary instance. A star in the Swan was perceived by Janson in 1600 to show fluctuations of light, and Montanari found in 1669 that Algol in Perseus shared the same peculiarity to a marked degree. Altogether the class embraced in 1782 half-a-dozen members. When it is added that a few star-couples had been noted in singularly, but it was supposed accidentally, close juxtaposition, and that the failure of repeated attempts to measure stellar parallaxes pointed to distances *at least* 400,000 times that of the earth from the sun,[7] the picture of sidereal science, when the last quarter of the eighteenth century began, is practically complete. It included three items of information: that the stars have motions, real or apparent; that they are immeasurably remote; and that a few shine with a periodically variable light. Nor were these scantily collected facts ordered into any promise of further development. They lay at once isolated and confused before the inquirer. They needed to be both multiplied and marshalled, and it seemed as if centuries of patient toil must elapse before any reliable conclusions could be derived from them. The sidereal world was thus the recognised domain of far-reaching speculations, which remained wholly uncramped by systematic research until Herschel entered upon his career as an observer of the heavens.

The greatest of modern astronomers was born at Hanover, November 15, 1738. He was the fourth child of Isaac Herschel, a hautboy-player in the band of the Hanoverian Guard, and was early trained to follow his father's profession. On the termination, however, of the disastrous campaign of 1757, his parents removed him from the regiment, there is reason to believe, in a somewhat unceremonious manner. Technically, indeed, he incurred the penalties of desertion, remitted—according to the Duke of Sussex's statement to Sir George Airy—by a formal pardon handed to him personally by George III. on his presentation in 1782.[8] At the age of nineteen, then, his military service having lasted four years, he came to England to seek his fortune. Of the life of struggle and privation which ensued little is known beyond the circumstances that in 1760 he was engaged in training the regimental band of the Durham Militia, and that in 1765 he was appointed organist at Halifax. In the following year he removed to Bath as oboist in Linley's orchestra, and in October 1767 was promoted to the post of organist in the Octagon Chapel. The tide of prosperity now began to flow for him. The most brilliant and modish society in England was at that time to be met at Bath, and the young Hanoverian quickly found himself a favourite and the fashion in it. Engagements multiplied upon him. He became director of the public concerts; he conducted oratorios, engaged singers, organised rehearsals, composed anthems, chants, choral services, besides undertaking private tuitions, at times amounting to thirty-five or even thirty-eight lessons a week. He in fact personified the musical activity of a place then eminently and energetically musical.

But these multifarious avocations did not take up the whole of his thoughts. His education, notwithstanding the poverty of his family, had not been neglected, and he had always greedily assimilated every kind of knowledge that came in his way. Now that he was a busy and a prosperous man, it might have been expected that he would run on in the deep professional groove laid down for him. On the contrary, his passion for learning seemed to increase with the diminution of the time available for its gratification. He studied Italian, Greek, mathematics; Maclaurin's Fluxions served to "unbend his mind"; Smith's Harmonics and Optics and Ferguson's Astronomy were the nightly companions of his pillow. What he read stimulated without satisfying his intellect. He desired not only to know, but to discover. In 1772 he hired a small telescope, and through it caught a preliminary glimpse of the rich and varied fields in which for so many years he was to expatiate. Henceforward the purpose of his life was fixed: it was to obtain "a knowledge of the construction of the heavens";[9] and this sublime ambition he cherished to the end.

A more powerful instrument was the first desideratum; and here his mechanical genius came to his aid. Having purchased the apparatus of a Quaker optician, he set about the manufacture of specula with a zeal which seemed to anticipate the wonders they were to disclose to him. It was not until fifteen years later that his grinding and polishing machines were invented, so the work had at that time to be entirely done by hand. During this tedious and laborious process (which could not be interrupted without injury, and lasted on one occasion sixteen hours), his strength was supported by morsels of food put into his mouth by his sister,[10] and his mind amused by her reading aloud to him the Arabian Nights, Don Quixote, or other light works. At length, after repeated failures, he found himself provided with a reflecting telescope—a 5-1/2-foot Gregorian—of his own construction. A copy of his first observation with it, on the great Nebula in Orion—an object of continual amazement and assiduous inquiry to him—is preserved by the Royal Society. It bears the date March 4, 1774.[11]

In the following year he executed his first "review of the heavens," memorable chiefly as an evidence of the grand and novel conceptions which already inspired him, and of the enthusiasm with which he delivered himself up to their guidance. Overwhelmed with professional engagements, he still contrived to snatch some moments for the stars; and between the acts at the theatre was often seen running from the harpsichord to his telescope, no doubt with that "uncommon precipitancy which accompanied all his actions."[12] He now rapidly increased the power and perfection of his telescopes. Mirrors of seven, ten, even twenty feet focal length, were successively completed, and unprecedented magnifying powers employed. His energy was unceasing, his perseverance indomitable. In the course of twenty-one years no less than 430 parabolic specula left his hands. He had entered upon his forty-second year when he sent his first paper to the *Philosophical Transactions*; yet during the ensuing thirty-nine years his contributions—

many of them elaborate treatises—numbered sixty-nine, forming a series of extraordinary importance to the history of astronomy. As a mere explorer of the heavens his labours were prodigious. He discovered 2,500 nebulæ, 806 double stars, passed the whole firmament in review four several times, counted the stars in 3,400 "gauge-fields," and executed a photometric classification of the principal stars, founded on an elaborate (and the first systematically conducted) investigation of their relative brightness. He was as careful and patient as he was rapid; spared no time and omitted no precaution to secure accuracy in his observations; yet in one night he would examine, singly and attentively, up to 400 separate objects.

The discovery of Uranus was a mere incident of the scheme he had marked out for himself—a fruit, gathered as it were by the way. It formed, nevertheless, the turning-point in his career. From a star-gazing musician he was at once transformed into an eminent astronomer; he was relieved from the drudgery of a toilsome profession, and installed as Royal Astronomer, with a modest salary of £200 a year; funds were provided for the construction of the forty-foot reflector, from the great space-penetrating power of which he expected unheard-of revelations; in fine, his future work was not only rendered possible, but it was stamped as authoritative.[13] On Whit-Sunday 1782, William and Caroline Herschel played and sang in public for the last time in St. Margaret's Chapel, Bath; in August of the same year the household was moved to Datchet, near Windsor, and on April 3, 1786, to Slough. Here happiness and honours crowded on the fortunate discoverer. In 1788 he married Mary, only child of James Baldwin, a merchant of the city of London, and widow of Mr. John Pitt—a lady whose domestic virtues were enhanced by the possession of a large jointure. The fruit of their union was one son, of whose work—the worthy sequel of his father's—we shall have to speak further on. Herschel was created a Knight of the Hanoverian Guelphic Order in 1816, and in 1821 he became the first President of the Royal Astronomical Society, his son being its first Foreign Secretary. But his health had now for some years been failing, and on August 25, 1822, he died at Slough, in the eighty-fourth year of his age, and was buried in Upton churchyard.

His epitaph claims for him the lofty praise of having "burst the barriers of heaven." Let us see in what sense this is true.

The first to form any definite idea as to the constitution of the stellar system was Thomas Wright, the son of a carpenter living at Byer's Green, near Durham. With him originated what has been called the "Grindstone Theory" of the universe, which regarded the Milky Way as the projection on the sphere of a stratum or disc of stars (our sun occupying a position near the centre), similar in magnitude and distribution to the lucid orbs of the constellations.[14] He was followed by Kant,[15] who transcended the views of his predecessor by assigning to nebulæ the position they long continued to occupy, rather on imaginative than scientific grounds, of "island universes," external to, and co-equal with, the Galaxy. Johann Heinrich Lambert,[16] a tailor's apprentice from Mühlhausen, followed, but independently. The conceptions of this remarkable man were grandiose, his intuitions bold, his views on some points a singular anticipation of subsequent discoveries. The sidereal world presented itself to him as a hierarchy of systems, starting from the planetary scheme, rising to throngs of suns within the circuit of the Milky Way—the "ecliptic of the stars," as he phrased it—expanding to include groups of many Milky Ways; these again combining to form the unit of a higher order of assemblage, and so onwards and upwards until the mind reels and sinks before the immensity of the contemplated creations.

"Thus everything revolves—the earth round the sun; the sun round the centre of his system; this system round a centre common to it with other systems; this group, this assemblage of systems, round a centre which is common to it with other groups of the same kind; and where shall we have done?"[17]

The stupendous problem thus speculatively attempted, Herschel undertook to grapple with experimentally. The upshot of this memorable inquiry was the inclusion, for the first time, within the sphere of human knowledge, of a connected body of facts, and inferences from facts, regarding the sidereal universe; in other words, the foundation of what may properly be called a science of the stars.

Tobias Mayer had illustrated the perspective effects which must ensue in the stellar sphere from a translation of the solar system, by comparing them to the separating in front and closing up behind of trees in a forest to the eye of an advancing spectator;[18] but the appearances which he thus correctly described he was unable to detect. By a more searching analysis of a smaller collection of proper motions, Herschel succeeded in rendering apparent the very consequences foreseen by Mayer. He showed, for example, that Arcturus and Vega did, in fact, appear to recede from, and Sirius and Aldebaran to approach, each other by very minute amounts; and, with a striking effort of divinatory genius, placed the "apex," or point of direction of the sun's motion, close to the star λ in the constellation Hercules,[19] within a few degrees of the spot indicated by later and indefinitely more refined methods of research. He resumed the subject in 1805,[20] but though employing a more rigorous method, was scarcely so happy in his result. In 1806,[21] he made a preliminary attempt to ascertain the speed of the sun's journey, fixing it, by doubtless much too low an estimate, at about three miles a second. Yet the validity of his general conclusion as to the line of solar travel, though long doubted, has been triumphantly confirmed. The question as to the "secular parallax" of the fixed stars was in effect answered.

With their *annual* parallax, however, the case was very different. The search for it had already led Bradley to the important discoveries of the aberration of light and the nutation of the earth's axis; it was now about to lead Herschel to a discovery of a different, but even more elevated character. Yet in neither case was the object primarily sought attained.

From the very first promulgation of the Copernician theory the seeming immobility of the stars had been urged as an argument against its truth; for if the earth really travelled in a vast orbit round the sun, objects in surrounding space should appear to change their positions, unless their distances were on a scale which, to the narrow ideas of the universe then prevailing, seemed altogether extravagant.[22] The existence of such apparent or "parallactic" displacements was accordingly regarded as the touchstone of the new views, and their detection became an object of earnest desire to those interested in maintaining them. Copernicus himself made the attempt; but with his "Triquetrum," a jointed wooden rule with the divisions marked in ink, constructed by himself,[23] he was hardly able to measure angles of ten minutes, far less fractions of a second. Galileo, a more impassioned defender of the system, strained his ears, as it were, from Arcetri, in his blind and sorrowful old age, for news of a discovery which two more centuries had still to wait for. Hooke believed he had found a parallax for the bright star in the Head of the Dragon; but was deceived. Bradley convinced himself that such effects were too minute for his instruments to measure. Herschel made a fresh attempt by a practically untried method.

It is a matter of daily experience that two objects situated at different distances seem to a beholder in motion to move relatively to each other. This principle Galileo, in the third of his Dialogues on the Systems of the World,[24] proposed to employ for the determination of stellar parallax; for two stars, lying apparently close together, but in reality separated by a great gulf of space, must shift their mutual positions when observed from opposite points of the earth's orbit; or rather, the remoter forms a virtually fixed point, to which the movements of the other can be conveniently referred. By this means complications were abolished more numerous and perplexing than Galileo himself was aware of, and the problem was reduced to one of simple micrometrical measurement. The "double-star method" was also suggested by James Gregory in 1675, and again by Wallis in 1693;[25] Huygens first, and afterwards Dr. Long of Cambridge (about 1750), made futile experiments with it; and it eventually led, in the hands of Bessel, to the successful determination of the parallax of 61 Cygni.

Its advantages were not lost upon Herschel. His attempt to assign definite distances to the nearest stars was no isolated effort, but part of the settled plan upon which his observations were conducted. He proposed to sound the heavens, and the first requisite was a knowledge of the length of his sounding-line. Thus it came about that his special attention was early directed to double stars.

"I resolved," he writes,[26] "to examine every star in the heavens with the utmost attention and a very high power, that I might collect such materials for this research as would enable me to fix my observations upon those that would best answer my end. The subject has already proved so extensive, and still promises so rich a harvest to those who are inclined to be diligent in the pursuit, that I cannot help inviting every lover of astronomy to join with me in observations that must inevitably lead to new discoveries."

The first result of these inquiries was a classed catalogue of 269 double stars presented to the Royal Society in 1782, followed, after three years, by an additional list of 434. In both these collections the distances separating the individuals of each pair were carefully measured, and (with a few exceptions) the angles made with the hour-circle by the lines joining their centres (technically called "angles of position") were determined with the aid of a "revolving-wire micrometer," specially devised for the purpose. Moreover, an important novelty was introduced by the observation of the various colours visible in the star-couples, the singular and vivid contrasts of which were now for the first time described.

Double stars were at that time supposed to be a purely optical phenomenon. Their components, it was thought, while in reality indefinitely remote from each other, were brought into fortuitous contiguity by the chance of lying nearly in the same line of sight from the earth. Yet Bradley had noticed a change of 30°, between 1718 and 1759, in the position-angle of the two stars forming Castor, and was thus within a hair's breadth of the discovery of their physical connection.[27] While the Rev. John Michell, arguing by the doctrine of probabilities, wrote as follows in 1767:—"It is highly probable in particular, and next to a certainty in general, that such double stars as appear to consist of two or more stars placed very near together, do really consist of stars placed near together, and under the influence of some general law."[28] And in 1784:[29] "It is not improbable that a few years may inform us that some of the great number of double, triple stars, etc., which have been observed by Mr. Herschel, are systems of bodies revolving about each other."

This remarkable speculative anticipation had a practical counterpart in Germany. Father Christian Mayer, a Jesuit astronomer at Mannheim, set himself, in January 1776, to collect examples of stellar pairs, and shortly after published the supposed discovery of "satellites" to many of the principal stars.[30] But his observations were neither exact nor prolonged enough to lead to useful results in such an inquiry. His disclosures were derided; his planet-stars treated as results of hallucination. *On n'a point cru à des choses aussi extraordinaires*, wrote Lalande[31] within one year of a better-grounded announcement to the same effect.

Herschel at first shared the general opinion as to the merely optical connection of double stars. Of this the purpose for which he made his collection is in itself sufficient evidence, since what may be called the *differential* method of parallaxes depends, as we have seen, for its efficacy upon disparity of distance. It was "much too soon," he declared in 1782,[32] "to form any theories of small stars revolving round large ones;" while in the year following,[33] he remarked that the identical proper motions of the two stars forming, to the naked eye, the single bright orb of Castor could only be explained as both equally due to the "systematic parallax" caused by the sun's movement in space. Plainly showing that the notion of a physical tie, compelling the two bodies to travel together, had not as yet entered into his speculations. But he was eminently open to conviction, and had, moreover, by observations unparalleled in amount as well as in kind, prepared ample materials for convincing himself and others. In 1802 he was able to announce the fact of his discovery, and in the two ensuing years, to lay in detail before the Royal Society proofs, gathered from the labours of a quarter of a century, of orbital revolution in the case of as many as fifty double stars, henceforth, he declared, to be held as real binary combinations, "intimately held together by the bond of mutual attraction."[34] The fortunate preservation in Dr. Maskelyne's note-book of a remark made by Bradley about 1759, to the effect that the line joining the components of Castor was an exact prolongation of that joining Castor with Pollux, added eighteen years to the time during which the pair were under scrutiny, and confirmed the evidence of change afforded by more recent observations. Approximate periods were fixed for many of the revolving suns—for Castor 342 years; for γ Leonis, 1200, δ Serpentis, 375, ε Bootis, 1681 years; ε Lyræ was noted as a "double-double-star," a change of relative situation having been detected in each of the two pairs composing the group; and the occultation was described of one star by another in the course of their mutual revolutions, as exemplified in 1795 by the rapidly circulating system of ζ Herculis.

Thus, by the sagacity and perseverance of a single observer, a firm basis was at last provided upon which to raise the edifice of sidereal science. The analogy long presumed to exist between the mighty star of our system and the bright points of light spangling the firmament was shown to be no fiction of the imagination, but a physical reality; the fundamental quality of attractive power was proved to be common to matter so far as the telescope was capable of exploring, and law, subordination, and regularity to give testimony of supreme and intelligent design no less in those limitless regions of space than in our narrow terrestrial home. The discovery was emphatically (in Arago's phrase) "one with a future," since it introduced the element of precise knowledge where more or less probable conjecture had previously held almost undivided sway; and precise knowledge tends to propagate itself and advance from point to point.

We have now to speak of Herschel's pioneering work in the skies. To explore with line and plummet the shining zone of the Milky Way, to delineate its form, measure its dimensions, and search out the intricacies of its construction, was the primary task of his life, which he never lost sight of, and to which all his other investigations were subordinate. He was absolutely alone in this bold endeavour. Unaided, he had to devise methods, accumulate materials, and sift out results. Yet it may safely be asserted that all the knowledge we possess on this sublime subject was prepared, and the greater part of it anticipated, by him.

The ingenious method of "star-gauging," and its issue in the delineation of the sidereal system as an irregular stratum of evenly-scattered suns, is the best-known part of his work. But it was, in truth, only a first rude approximation, the principle of which maintained its credit in the literature of astronomy a full half-century after its abandonment by its author. This principle was the general equality of star distribution. If equal portions of space really held equal numbers of stars, it is obvious that the number of stars visible in any particular direction would be strictly proportional to the range of the system in that direction, apparent accumulation being produced by real extent. The process of "gauging the heavens," accordingly, consisted in counting the stars in successive telescopic fields, and calculating thence the depths of space necessary to contain them. The result of 3,400 such operations was the plan of the Galaxy familiar to every reader of an astronomical text-book. Widely-varying evidence was, as might have been expected, derived from an examination of different portions of the sky. Some fields of view were almost blank, while others (in or near the Milky Way) blazed with the radiance of many hundred stars compressed into an area about one-fourth that of the full-moon. In the most crowded parts 116,000 were stated to have been passed in review within a quarter of an hour. Here the "length of his sounding-line" was estimated by Herschel at about 497 times the distance of Sirius—in other words, the bounding orb, or farthest sun of the system in that direction, so far as could be seen with the 20-foot reflector, was thus inconceivably remote. But since the distance of Sirius, no less than of every other fixed star, was as yet an unknown quantity, the dimensions inferred for the Galaxy were of course purely relative; a knowledge of its form and structure might (admitting the truth of the fundamental hypothesis) be obtained, but its real or absolute size remained altogether undetermined.

Even as early as 1785, however, Herschel perceived traces of a tendency which completely invalidated the supposition of any approach to an average uniformity of distribution. This was the action of what he called a "clustering power" in the Milky Way. "Many gathering clusters"[35] were already discernible to him even while he endeavoured to obtain a "true *mean* result" on the assumption that each star in space was separated from its neighbours as widely as the sun from Sirius. "It appears," he wrote in 1789, "that the heavens consist of regions where suns are gathered into separate systems"; and in certain assemblages he was able to trace "a course or tide of stars setting towards a centre," denoting, not doubtfully, the presence of attractive forces.[36] Thirteen years later, he described our sun and his constellated companions as surrounded by "a magnificent collection of innumerable stars, called the Milky Way, which must occasion a very powerful balance of opposite attractions to hold the intermediate stars at rest. For though our sun, and all the stars we see, may truly be said to be in the plane of the Milky Way, yet I am now convinced, by a long inspection and continued examination of it, that the Milky Way itself consists of stars very differently scattered from those which are immediately about us." "This immense aggregation," he added, "is by no means uniform. Its component stars show evident signs of clustering together into many separate allotments."[37]

The following sentences, written in 1811, contain a definite retractation of the view frequently attributed to him:—

"I must freely confess," he says, "that by continuing my sweeps of the heavens my opinion of the arrangement of the stars and their magnitudes, and of some other particulars, has undergone a gradual change; and indeed, when the novelty of the subject is considered, we cannot be surprised that many things formerly taken for granted should on examination prove to be different from what they were generally but incautiously supposed to be. For instance, an equal scattering of the stars may be admitted in certain calculations; but when we examine the Milky Way, or the closely compressed clusters of stars of which my catalogues have recorded so many instances, this supposed equality of scattering must be given up."[38]

Another assumption, the fallacy of which he had not the means of detecting since become available, was retained by him to the end of his life. It was that the brightness of a star afforded an approximate measure of its distance. Upon this principle he founded in 1817 his method of "limiting apertures,"[39] by which two stars, brought into view in two precisely similar telescopes, were "equalised" by covering a certain portion of the object-glass collecting the more brilliant rays. The distances of the orbs compared were then taken to be in the ratio of the reduced to the original apertures of the instruments with which they were examined. If indeed the absolute lustre of each were the same, the result might be accepted with confidence; but since we have no warrant for assuming a "standard star" to facilitate our computations, but much reason to suppose an indefinite range, not only of size but of intrinsic brilliancy, in the suns of our firmament, conclusions drawn from such a comparison are entirely worthless.

In another branch of sidereal science besides that of stellar aggregation, Herschel may justly be styled a pioneer. He was the first to bestow serious study on the enigmatical objects known as "nebulæ." The history of the acquaintance of our race with them is comparatively short. The only one recognised before the invention of the telescope was that in the girdle of Andromeda, certainly familiar in the middle of the tenth century to the Persian astronomer Abdurrahman Al-Sûfi; and marked with dots on Spanish and Dutch constellation-charts of the fourteenth and fifteenth centuries.[40] Yet so little was it noticed that it might practically be said—as far as Europe is concerned—to have been discovered in 1612 by Simon Marius (Mayer of Genzenhausen), who aptly described its appearance as that of a "candle shining through horn." The first mention of the great Orion nebula is by a Swiss Jesuit named Cysatus, who succeeded Father Scheiner in the chair of mathematics at Ingolstadt. He used it, apparently without any suspicion of its novelty, as a term of comparison for the comet of December 1618.[41] A novelty, nevertheless, to astronomers it still remained in 1656, when Huygens discerned, "as it were, an hiatus in the sky, affording a glimpse of a more luminous region beyond."[42] Halley in 1716 knew of six nebulæ, which he believed to be composed of a "lucid medium" diffused through the ether of space.[43] He appears, however, to have been unacquainted with some previously noticed by Hevelius. Lacaille brought back with him from the Cape a list of forty-two—the first-fruits of observation in Southern skies—arranged in three numerically equal classes;[44] and Messier (nicknamed by Louis XV. the "ferret of comets"), finding such objects a source of extreme perplexity in the pursuit of his chosen game, attempted to eliminate by methodising them, and drew up a catalogue comprising, in 1781, 103 entries.[45]

These preliminary attempts shrank into insignificance when Herschel began to "sweep the heavens" with his giant telescopes. In 1786 he presented to the Royal Society a descriptive catalogue of 1,000 nebulæ and clusters, followed, three years later, by a second of as many more; to which he added in 1802 a further gleaning of 500. On the subject of their nature his views underwent a remarkable change. Finding that his potent instruments resolved into stars many nebulous patches in which no signs of such a structure had previously been discernible, he naturally concluded that "resolvability" was merely a question of distance and telescopic power. He was (as he said himself) led on by almost imperceptible degrees from evident clusters, such as the Pleiades, to spots without a trace of stellar formation, the gradations being so well connected as to leave no doubt that all these phenomena were equally stellar. The singular variety of their appearance was thus described by him:—

"I have seen," he says, "double and treble nebulæ variously arranged; large ones with small, seeming attendants; narrow, but much extended lucid nebulæ or bright dashes; some of the shape of a fan, resembling an electric brush, issuing from a lucid point; others of the cometic shape, with a seeming nucleus in the centre, or like cloudy stars surrounded with a nebulous atmosphere; a different sort, again, contain a nebulosity of the milky kind, like that wonderful, inexplicable phenomenon about θ Orionis; while others shine with a fainter, mottled kind of light, which denotes their being resolvable into stars."[46]

"These curious objects" he considered to be "no less than whole sidereal systems,"[47] some of which might "well outvie our Milky Way in grandeur." He admitted, however, a wide diversity in condition as well as compass. The system to which our sun belongs he described as "a very extensive branching congeries of many millions of stars, which probably owes its origin to many remarkably large as well as pretty closely scattered small stars, that may have drawn together the rest."[48] But the continued action of this same "clustering power" would, he supposed, eventually lead to the breaking-up of the original majestic Galaxy into two or three hundred separate groups, already visibly gathering. Such minor nebulæ, due to the "decay" of other "branching nebulæ" similar to our own, he recognised by the score, lying, as it were, stratified in certain quarters of the sky. "One of these nebulous beds," he informs us, "is so rich that in passing through a section of it, in the time of only thirty-six minutes, I detected no less than thirty-one nebulæ, all distinctly visible upon a fine blue sky." The stratum of Coma Berenices he judged to be the nearest to our system of such layers; nor did the marked aggregation of nebulæ towards both poles of the circle of the Milky Way escape his notice.

By a continuation of the same process of reasoning, he was enabled (as he thought) to trace the life-history of nebulæ from a primitive loose and extended formation, through clusters of gradually increasing compression, down to the kind named by him "Planetary" because of the defined and uniform discs which they present. These he regarded as "very aged, and drawing on towards a period of change or dissolution."[49]

"This method of viewing the heavens," he concluded, "seems to throw them into a new kind of light. They now are seen to resemble a luxuriant garden which contains the greatest variety of productions in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For, to continue the simile which I have borrowed from the vegetable kingdom, is it not almost the same thing whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view?"[50]

But already this supposed continuity was broken. After mature deliberation on the phenomena presented by nebulous stars, Herschel was induced, in 1791, to modify essentially his original opinion.

"When I pursued these researches," he says, "I was in the situation of a natural philosopher who follows the various species of animals and insects from the height of their perfection down to the lowest ebb of life; when, arriving at the vegetable kingdom, he can scarcely point out to us the precise boundary where the animal ceases and the plant begins; and may even go so far as to suspect them not to be essentially different. But, recollecting himself, he compares, for instance, one of the human species to a tree, and all doubt upon the subject vanishes before him. In the same manner we pass through gentle steps from a coarse cluster of stars, such as the Pleiades … till we find ourselves brought to an object such as the nebula in Orion, where we are still inclined to remain in the once adopted idea of stars exceedingly remote and inconceivably crowded, as being the occasion of that remarkable appearance. It seems, therefore, to require a more dissimilar object to set us right again. A glance like that of the naturalist, who casts his eye from the perfect animal to the perfect vegetable, is wanting to remove the veil from the mind of the astronomer. The object I have mentioned above is the phenomenon that was wanting for this purpose. View, for instance, the 19th cluster of my 6th class, and afterwards cast your eye on this cloudy star, and the result will be no less decisive than that of the naturalist we have alluded to. Our judgment, I may venture to say, will be, that *the nebulosity about the star is not of a starry nature*."[51]

The conviction thus arrived at of the existence in space of a widely diffused "shining fluid" (a conviction long afterwards fully justified by the spectroscope) led him into a field of endless speculation. What was its nature? Should it "be compared to the coruscation of the electric fluid in the aurora borealis? or to the more magnificent cone of the zodiacal light?" Above all, what was its function in the cosmos? And on this point he already gave a hint of the direction in which his mind was moving by the remark that this self-luminous matter seemed "more fit to produce a star by its condensation, than to depend on the star for its existence."[52]

This was not a novel idea. Tycho Brahe had tried to explain the blaze of the star of 1572 as due to a sudden concentration of nebulous material in the Milky Way, even pointing out the space left dark and void by the withdrawal of the luminous stuff; and Kepler, theorising on a similar stellar apparition in 1604, followed nearly in the same track. But under Herschel's treatment the nebular origin of stars first acquired the consistency of a formal theory. He meditated upon it long and earnestly, and in two elaborate treatises, published respectively in 1811 and 1814, he at length set forth the arguments in its favour. These rested entirely upon the "principle of continuity." Between the successive classes of his assortment of developing objects there was, as he said, "perhaps not so much difference as would be in an annual description of the human figure, were it given from the birth of a child till he comes to be a man in his prime."[53] From diffused nebulosity, barely visible in the most powerful light-gathering instruments, but which he estimated to cover nearly 152 square degrees of the heavens,[54] to planetary nebulæ, supposed to be already centrally solid, instances were alleged of every stage and phase of condensation. The validity of his reasoning, however, was evidently impaired by his confessed inability to distinguish between the dim rays of remote clusters and the milky light of true gaseous nebulæ.

It may be said that such speculations are futile in themselves, and necessarily barren of results. But they gratify an inherent tendency of the human mind, and, if pursued in a becoming spirit, should be neither reproved nor disdained. Herschel's theory still holds the field, the testimony of recent discoveries with regard to it having proved strongly confirmatory of its principle, although not of its details. Strangely enough, it seems to have been propounded in complete independence of Laplace's nebular hypothesis as to the origin of the solar system. Indeed, it dated, as we have seen, in its first inception, from 1791, while the French geometrician's view was not advanced until 1796.

We may now briefly sum up the chief results of Herschel's long years of "watching the heavens." The apparent motions of the stars had been disentangled; one portion being clearly shown to be due to a translation towards a point in the constellation Hercules of the sun and his attendant planets; while a large balance of displacement was left to be accounted for by real movements, various in extent and direction, of the stars themselves. By the action of a central force similar to, if not identical with, gravity, suns of every degree of size and splendour, and sometimes brilliantly contrasted in colour, were seen to be held together in systems, consisting of two, three, four, even six members, whose revolutions exhibited a wide range of variety both in period and in orbital form. A new department of physical astronomy was thus created,[55] and rigid calculation for the first time made possible within the astral region. The vast problem of the arrangement and relations of the millions of stars forming the Milky Way was shown to be capable of experimental treatment, and of at least partial solution, notwithstanding the variety and complexity seen to prevail, to an extent previously undreamt of, in the arrangement of that majestic system. The existence of a luminous fluid, diffused through enormous tracts of space, and intimately associated with stellar bodies, was virtually demonstrated, and its place and use in creation attempted to be divined by a bold but plausible conjecture. Change on a stupendous scale was inferred or observed to be everywhere in progress. Periodical stars shone out and again decayed; progressive ebbings or flowings of light were indicated as probable in many stars under no formal suspicion of variability; forces were everywhere perceived to be at work, by which the very structure of the heavens themselves must be slowly but fundamentally modified. In all directions groups were seen to be formed or forming; tides and streams of suns to be setting towards powerful centres of attraction; new systems to be in process of formation, while effete ones hastened to decay or regeneration when the course appointed for them by Infinite Wisdom was run. And thus, to quote the words of the observer who “had looked farther into space than ever human being did before him,”[56] the state into which the incessant action of the clustering power has brought the Milky Way at present, is a kind of chronometer that may be used to measure the time of its past and future existence; and although we do not know the rate of going of this mysterious chronometer, it is nevertheless certain that, since the breaking-up of the parts of the Milky Way affords a proof that it cannot last for ever, it equally bears witness that its past duration cannot be admitted to be infinite.[57]

FOOTNOTES:

[3] *Phil. Trans.*, vol. xxx., p. 737.

[4] Out of eighty stars compared, fifty-seven were found to have changed their places by more than 10″. Lesser discrepancies were at that time regarded as falling within the limits of observational error. *Tobiæ Mayeri Op. Inedita*, t. i., pp. 80, 81, and Herschel in *Phil. Trans.*, vol. lxxiii., pp. 275-278.

[5] *Posthumous Works*, p. 701.

[6] Arago in *Annuaire du Bureau des Longitudes*, 1842, p. 313.

[7] Bradley to Halley, *Phil. Trans.*, vol. xxxv. (1728), p. 660. His observations were directly applicable to only two stars, γ Draconis and η Ursæ Majoris, but some lesser ones were included in the same result.

[8] Holden, *Sir William Herschel, his Life and Works*, p. 17.

[9] *Phil. Trans.*, vol. ci., p. 269.

[10] Caroline Lucretia Herschel, born at Hanover, March 16, 1750, died in the same place, January 9, 1848. She came to England in 1772, and was her brother's devoted assistant, first in his musical undertakings, and afterwards, down to the end of his life, in his astronomical labours.

[11] Holden, *op. cit.*, p. 39.

[12] *Memoir of Caroline Herschel*, p. 37.

[13] See Holden's *Sir William Herschel*, p. 54.

[14] *An Original Theory or New Hypothesis of the Universe*, London, 1750. See also De Morgan's summary of his views in *Philosophical Magazine*, April, 1848.

[15] *Allgemeine Naturgeschichte und Theorie des Himmels*, 1755.

[16] *Cosmologische Briefe*, Augsburg, 1761.

[17] *The System of the World*, p. 125, London, 1800 (a translation of *Cosmologische Briefe*). Lambert regarded nebulæ as composed of stars crowded together, but *not* as external universes. In the case of the Orion nebula, indeed, he throws out such a conjecture, but afterwards suggests that it may form a centre for that one of the subordinate systems composing the Milky Way to which our sun belongs.

[18] *Opera Inedita*, t. i., p. 79.

[19] *Phil. Trans.*, vol. lxxiii. (1783), p. 273. Pierre Prévost's similar investigation, communicated to the Berlin Academy of Sciences four months later, July 3, 1783, was inserted in the *Memoirs* of that body for 1781, and thus *seems* to claim a priority not its due. Georg Simon Klügel at Halle gave about the same time an analytical demonstration of Herschel's result. Wolf, *Gesch. der Astronomie*, p. 733.

[20] *Phil. Trans.*, vol. xcv., p. 233.

[21] *Ibid.*, vol. xcvi., p. 205.

[22] "Ingens bolus devorandus est," Kepler admitted to Herwart in May, 1603.

[23] Described in "Præfatio Editoris" to *De Revolutionibus*, p. xix. (ed. 1854).

[24] *Opere*, t. i., p. 415.

[25] *Phil. Trans.*, vol. xvii., p. 848.

[26] *Ibid.*, vol. lxxii., p. 97.

[27] Doberck, *Observatory*, vol. ii., p. 110.

[28] *Phil. Trans.*, vol. lvii., p. 249.

[29] *Ibid.*, vol. lxxiv., p. 56.

[30] *Beobachtungen von Fixsterntrabanten*, 1778; and *De Novis in Cœlo Sidereo Phænomenis*, 1779.

[31] *Bibliographie*, p. 569.

[32] *Phil. Trans.*, vol. lxxii., p. 162.

[33] *Ibid.*, vol. lxxiii., p. 272.

[34] *Ibid.*, vol. xciii., p. 340.

[35] *Phil. Trans.*, vol. lxxv., p. 255.

[36] *Ibid.*, vol. lxxix., pp. 214, 222.

[37] *Ibid.*, vol. xcii., pp. 479, 495.

[38] *Phil. Trans.*, vol. ci., p. 269.

[39] *Ibid.*, vol. cvii., p. 311.

[40] Bullialdus, *De Nebulosâ Stellâ in Cingulo Andromedæ* (1667); see also G. P. Bond, *Mém. Am. Ac.*, vol. iii., p. 75, Holden's Monograph on the Orion Nebula, *Washington Observations*, vol. xxv., 1878 (pub. 1882), and Lady Huggins's drawing, *Atlas of Spectra*, p. 119.

[41] *Mathemata Astronomica*, p. 75.

[42] *Systema Saturnium*, p. 9.

[43] *Phil. Trans.*, vol. xxix., p. 390.

[44] *Mém. Ac. des Sciences*, 1755.

[45] *Conn. des Temps*, 1784 (pub. 1781), p. 227. A previous list of forty-five had appeared in *Mém. Ac. des Sciences*, 1771.

[46] *Phil. Trans.*, vol. lxxiv., p. 442.

[47] *Ibid.*, vol. lxxix., p. 213.

[48] *Ibid.*, vol. lxxv., p. 254.

[49] *Ibid.*, vol. lxxix., p. 225.

[50] *Phil. Trans.*, vol. lxxix., p. 226.

[51] *Ibid.*, vol. lxxxi., p. 72.

[52] *Ibid.*, p. 85.

[53] *Phil. Trans.*, vol. ci., p. 271.

[54] *Ibid.*, p. 277.

[55] J. Herschel, *Phil. Trans.*, vol. cxvi., part iii., p. 1.

[56] His own words to the poet Campbell cited by Holden, *Life and Works*, p. 109.

[57] *Phil. Trans.*, vol. civ., p. 283.

CHAPTER II

PROGRESS OF SIDEREAL ASTRONOMY

We have now to consider labours of a totally different character from those of Sir William Herschel. Exploration and discovery do not constitute the whole business of astronomy; the less adventurous, though not less arduous, task of gaining a more and more complete mastery over the problems immemorially presented to her, may, on the contrary, be said to form her primary duty. A knowledge of the movements of the heavenly bodies has, from the earliest times, been demanded by the urgent needs of mankind; and science finds its advantage, as in many cases it has taken its origin, in condescension to practical claims. Indeed, to bring such knowledge as near as possible to absolute precision has been defined by no mean authority[58] as the true end of astronomy.

Several causes concurred about the beginning of the last century to give a fresh and powerful impulse to investigations having this end in view. The rapid progress of theory almost compelled a corresponding advance in observation; instrumental improvements rendered such an advance possible; Herschel's discoveries quickened public interest in celestial inquiries; royal, imperial, and grand-ducal patronage widened the scope of individual effort. The heart of the new movement was in Germany. Hitherto the observatory of Flamsteed and Bradley had been the acknowledged centre of practical astronomy; Greenwich observations were the standard of reference all over Europe; and the art of observing prospered in direct proportion to the fidelity with which Greenwich methods were imitated. Dr. Maskelyne, who held the post of Astronomer Royal during forty-six years (from 1765 to 1811), was no unworthy successor to the eminent men who had gone before him. His foundation of the *Nautical Almanac* (in 1767) alone constitutes a valid title to fame; he introduced at the Observatory the important innovation of the systematic publication of results; and the careful and prolonged series of observations executed by him formed the basis of the improved theories, and corrected tables of the celestial movements, which were rapidly being brought to completion abroad. His catalogue of thirty-six "fundamental" stars was besides excellent in its way, and most serviceable. Yet he was devoid of Bradley's instinct for divining the needs of the future. He was fitted rather to continue a tradition than to found a school. The old ways were dear to him; and, indefatigable as he was, a definite purpose was wanting to compel him, by its exigencies, along the path of progress. Thus, for almost fifty years after Bradley's death, the acquisition of a small achromatic[59] was the only notable change made in the instrumental equipment of the Observatory. The transit, the zenith sector, and the mural quadrant, with which Bradley had done his incomparable work, retained their places long after they had become deteriorated by time and obsolete by the progress of invention; and it was not until the very close of his career that Maskelyne, compelled by Pond's detection of serious errors, ordered a Troughton's circle, which he did not live to employ.

Meanwhile, the heavy national disasters with which Germany was overwhelmed in the early part of the nineteenth century seemed to stimulate rather than impede the intellectual revival already for some years in progress there. Astronomy was amongst the first of the sciences to feel the new impulse. By the efforts of Bode, Olbers, Schröter, and Von Zach, just and elevated ideas on the subject were propagated, intelligence was diffused, and a firm ground prepared for common action in mutual sympathy and disinterested zeal. They received powerful aid through the foundation, in 1804, by a young artillery officer named Von Reichenbach, of an Optical and Mechanical Institute at Munich. Here the work of English instrumental artists was for the first time rivalled, and that of English opticians—when Fraunhofer entered the new establishment—far surpassed. The development given to the refracting telescope by this extraordinary man was indispensable to the progress of that fundamental part of astronomy which consists in the exact determination of the places of the heavenly bodies. Reflectors are brilliant engines of discovery, but they lend themselves with difficulty to the prosaic work of measuring right ascensions and polar distances. A signal improvement in the art of making and working flint-glass thus most opportunely coincided with the rise of a German school of scientific mechanicians, to furnish the instrumental means needed for the reform which was at hand. Of the leader of that reform it is now time to speak.

Friedrich Wilhelm Bessel was born at Minden, in Westphalia, July 22, 1784. A certain taste for figures, coupled with a still stronger distaste for the Latin accidence, directed his inclination and his father's choice towards a mercantile career. In his fifteenth year, accordingly, he entered the house of Kuhlenkamp and Sons, in Bremen, as an apprenticed clerk. He was now thrown completely upon his own resources. From his father, a struggling Government official, heavily weighted with a large family, he was well aware that he had nothing to expect; his dormant faculties were roused by the necessity for self-dependence, and he set himself to push manfully forward along the path that lay before him. The post of supercargo on one of the trading expeditions sent out from the Hanseatic towns to China and the East Indies was the aim of his boyish ambition, for the attainment of which he sought to qualify himself by the industrious acquisition of suitable and useful knowledge. He learned English in two or three months; picked up Spanish with the casual aid of a gunsmith's apprentice; studied the geography of the distant lands which he hoped to visit; collected information as to their climates, inhabitants, products, and the courses of trade. He desired to add some acquaintance with the art (then much neglected) of taking observations at sea; and thus, led on from navigation to astronomy, and from astronomy to mathematics, he groped his way into a new world.

It was characteristic of him that the practical problems of science should have attracted him before his mind was as yet sufficiently matured to feel the charm of its abstract beauties. His first attempt at observation was made with a sextant, rudely constructed under his own directions, and a common clock. Its object was the determination of the longitude of Bremen, and its success, he tells us himself,[60] filled him with a rapture of delight, which, by confirming his tastes, decided his destiny. He now eagerly studied Bode's *Jahrbuch* and Von Zach's *Monatliche Correspondenz*, overcoming each difficulty as it arose with the aid of Lalande's *Traité d'Astronomie*, and supplying, with amazing rapidity, his early deficiency in mathematical training. In two years he was able to attack a problem which would have tasked the patience, if not the skill, of the most experienced astronomer. Amongst the Earl of Egremont's papers Von Zach had discovered Harriot's observations on Halley's comet at its appearance in 1607, and published them as a supplement to Bode's Annual. With an elaborate care inspired by his youthful ardour, though hardly merited by their loose nature, Bessel deduced from them an orbit for that celebrated body, and presented the work to Olbers, whose reputation in cometary researches gave a special fitness to the proffered homage. The benevolent physician-astronomer of Bremen welcomed with surprised delight such a performance emanating from such a source. Fifteen years previously, the French Academy had crowned a similar work; now its equal was produced by a youth of twenty, busily engaged in commercial pursuits, self-taught, and obliged to snatch from sleep the hours devoted to study. The paper was immediately sent to Von Zach for publication, with a note from Olbers explaining the circumstances of its author; and the name of Bessel became the common property of learned Europe.

He had, however, as yet no intention of adopting astronomy as his profession. For two years he continued to work in the counting-house by day, and to pore over the *Mécanique Céleste* and the Differential Calculus by night. But the post of assistant in Schröter's observatory at Lilienthal having become vacant by the removal of Harding to Göttingen in 1805, Olbers procured for him the offer of it. It was not without a struggle that he resolved to exchange the desk for the telescope. His reputation with his employers was of the highest; he had thoroughly mastered the details of the business, which his keen practical intelligence followed with lively interest; his years of apprenticeship were on the point of expiring, and an immediate, and not unwelcome prospect of comparative affluence lay before him. The love of science, however, prevailed; he chose poverty and the stars, and went to Lilienthal with a salary of a hundred thalers yearly. Looking back over his life's work, Olbers long afterwards declared that the greatest service which he had rendered to astronomy was that of having discerned, directed, and promoted the genius of Bessel.[61]

For four years he continued in Schröter's employment. At the end of that time the Prussian Government chose him to superintend the erection of a new observatory at Königsberg, which after many vexatious delays, caused by the prostrate condition of the country, was finished towards the end of 1813. Königsberg was the first really efficient German observatory. It became, moreover, a centre of improvement, not for Germany alone, but for the whole astronomical world. During two-and-thirty years it was the scene of Bessel's labours, and Bessel's labours had for their aim the reconstruction, on an amended and uniform plan, of the entire science of observation.

A knowledge of the places of the stars is the foundation of astronomy.[62] Their configuration lends to the skies their distinctive features, and marks out the shifting tracks of more mobile objects with relatively fixed, and generally unvarying points of light. A more detailed and accurate acquaintance with the stellar multitude, regarded from a purely uranographical point of view, has accordingly formed at all times a primary object of celestial science, and was, during the last century, cultivated with a zeal and success by which all previous efforts were dwarfed into insignificance. In Lalande's *Histoire Céleste*, published in 1801, the places of no less than 47,390 stars were given, but in the rough, as it were, and consequently needing laborious processes of calculation to render them available for exact purposes. Piazzi set an example of improved methods of observation, resulting in the publication, in 1803 and 1814, of two catalogues of about 7,600 stars—the second being a revision and enlargement of the first—which for their time were models of what such works should be.[63] Stephen Groombridge at Blackheath was similarly and most beneficially active. But something more was needed than the diligence of individual observers. A systematic reform was called for; and it was this which Bessel undertook and carried through.

Direct observation furnishes only what has been called the "raw material" of the positions of the heavenly bodies.[64] A number of highly complex corrections have to be applied before their *mean* can be disengaged from their *apparent* places on the sphere. Of these, the most considerable and familiar is atmospheric refraction, by which objects seem to stand higher in the sky than they in reality do, the effect being evanescent at the zenith, and attaining, by gradations varying with conditions of pressure and temperature, a maximum at the horizon. Moreover, the points to which measurements are referred are themselves in motion, either continually in one direction, or periodically to and fro. The *precession* of the equinoxes is slowly progressive, or rather retrogressive; the *nutation* of the pole oscillatory in a period of about eighteen years. Added to which, the non-instantaneous transmission of light, combined with the movement of the earth in its orbit, causes a small annual displacement known as *aberration*.

Now it is easy to see that any uncertainty in the application of these corrections saps the very foundations of exact astronomy. Extremely minute quantities, it is true, are concerned; but the life and progress of modern celestial science depends upon the sure recognition of extremely minute quantities. In the early years of the nineteenth century, however, no uniform system of "reduction" (so the complete correction of observational results is termed) had been established. Much was left to the individual caprice of observers, who selected for the several "elements" of reduction such values as seemed best to themselves. Hence arose much hurtful confusion, tending to hinder united action and mar the usefulness of laborious researches. For this state of things, Bessel, by the exercise of consummate diligence, sagacity, and patience, provided an entirely satisfactory remedy.

His first step was an elaborate investigation of the precious series of observations made by Bradley at Greenwich from 1750 until his death in 1762. The catalogue of 3,222 stars which he extracted from them gave the earliest example of the systematic reduction on a uniform plan of such a body of work. It is difficult, without entering into details out of place in a volume like the present, to convey an idea of the arduous nature of this task. It involved the formation of a theory of the errors of each of Bradley's instruments, and a difficult and delicate inquiry into the true value of each correction to be applied, before the entries in the Greenwich journals could be developed into a finished and authentic catalogue. Although completed in 1813, it was not until five years later that the results appeared with the proud, but not inappropriate title of *Fundamenta Astronomiæ*. The eminent value of the work consisted in this, that by providing a mass of entirely reliable information as to the state of the heavens at the epoch 1755, it threw back the beginning of *exact* astronomy almost half a century. By comparison with Piazzi's catalogues the amount of precession was more accurately determined, the proper motions of a considerable number of stars became known with certainty, and definite prediction—the certificate of initiation into the secrets of Nature—at last became possible as regards the places of the stars. Bessel's final improvements in the methods of reduction were published in 1830 in his *Tabulæ Regiomontanæ*. They not only constituted an advance in accuracy, but afforded a vast increase of facility in application, and were at once and everywhere adopted. Thus astronomy became a truly universal science; uncertainties and disparities were banished, and observations made at all times and places rendered mutually comparable.[65]

More, however, yet remained to be done. In order to verify with greater strictness the results drawn from the Bradley and Piazzi catalogues, a third term of comparison was wanted, and this Bessel undertook to supply. By a course of 75,011 observations, executed during the years 1821-33, with the utmost nicety of care, the number of accurately known stars was brought up to above 50,000, and an ample store of trustworthy facts laid up for the use of future astronomers. In this department Argelander, whom he attracted from finance to astronomy, and trained in his own methods, was his assistant and successor. The great "Bonn Durchmusterung,"[66] in which 324,198 stars visible in the northern hemisphere are enumerated, and the corresponding "Atlas" published in 1857-63, constituting a picture of our sidereal surroundings of heretofore unapproached completeness, may be justly said to owe their origin to Bessel's initiative, and to form a sequel to what he commenced.

But his activity was not solely occupied with the promotion of a comprehensive reform in astronomy; it embraced special problems as well. The long-baffled search for a parallax of the fixed stars was resumed with fresh zeal as each mechanical or optical improvement held out fresh hopes of a successful issue. Illusory results abounded. Piazza in 1805 perceived, as he supposed, considerable annual displacements in Vega, Aldebaran, Sirius, and Procyon; the truth being that his instruments were worn out with constant use, and could no longer be depended upon.[67] His countryman, Calandrelli, was similarly deluded. The celebrated controversy between the Astronomer Royal and Dr. Brinkley, Director of the Dublin College Observatory, turned on the same subject. Brinkley, who was in possession of a first-rate meridian-circle, believed himself to have discovered relatively large parallaxes for four of the brightest stars; Pond, relying on the testimony of the Greenwich instruments, asserted their nullity. The dispute, protracted for fourteen years, from 1810 until 1824, was brought to no definite conclusion; but the strong presumption on the negative side was abundantly justified in the event.

There was good reason for incredulity in the matter of parallaxes. Announcements of their detection had become so frequent as to be discredited before they were disproved; and Struve, who investigated the subject at Dorpat in 1818-21, had clearly shown that the quantities concerned were too small to come within the reliable measuring powers of any instrument then in use. Already, however, the means were being prepared of giving to those powers a large increase.

On the 21st July, 1801, two old houses in an alley of Munich tumbled down, burying in their ruins the occupants, of whom one alone was extricated alive, though seriously injured. This was an orphan lad of fourteen named Joseph Fraunhofer. The Elector Maximilian Joseph was witness of the scene, became interested in the survivor, and consoled his misfortune with a present of eighteen ducats. Seldom was money better bestowed. Part of it went to buy books and a glass-polishing machine, with the help of which young Fraunhofer studied mathematics and optics, and secretly exercised himself in the shaping and finishing of lenses; the remainder purchased his release from the tyranny of one Weichselberger, a looking-glass maker by trade, to whom he had been bound apprentice on the death of his parents. A period of struggle and privation followed, during which, however, he rapidly extended his acquirements; and was thus eminently fitted for the task awaiting him, when, in 1806, he entered the optical department of the establishment founded two years previously by Von Reichenbach and Utzschneider. He now zealously devoted himself to the improvement of the achromatic telescope; and, after a prolonged study of the theory of lenses, and many toilsome experiments in the manufacture of flint-glass, he succeeded in perfecting, December 12, 1817, an object-glass of exquisite quality and finish, 9-1/2 inches in diameter, and of 14 feet focal length.

This (as it was then considered) gigantic lens was secured by Struve for the Russian Government, and the “great Dorpat refractor”—the first of the large achromatics which have played such an important part in modern astronomy—was, late in 1824, set up in the place which it still occupies. By ingenious improvements in mounting and fitting, it was adapted to the finest micrometrical work, and thus offered unprecedented facilities both for the examination of double stars (in which Struve chiefly employed it), and for such subtle measurements as might serve to reveal or disprove the existence of a sensible stellar parallax. Fraunhofer, moreover, constructed for the observatory at Königsberg the first really available heliometer. The principle of this instrument (termed with more propriety a “divided object-glass micrometer”) is the separation, by a strictly measurable amount, of two distinct images of the same object. If a double star, for instance, be under examination, the two half-lenses into which the object-glass is divided are shifted until the upper star (say) in one image is brought into coincidence with the lower star in the other, when their distance apart becomes known by the amount of motion employed.[68]

This virtually new engine of research was delivered and mounted in 1829, three years after the termination of the life of its deviser. The Dorpat lens had brought to Fraunhofer a title of nobility and the sole management of the Munich Optical Institute (completely separated since 1814 from the mechanical department). What he had achieved, however, was but a small part of what he meant to achieve. He saw before him the possibility of nearly quadrupling the light-gathering capacity of the great achromatic acquired by Struve; he meditated improvements in reflectors as important as those he had already effected in refractors; and was besides eagerly occupied with investigations into the nature of light, the momentous character of which we shall by-and-by have an opportunity of estimating. But his health was impaired, it is said, from the weakening effects of his early accident, combined with excessive and unwholesome toil, and, still hoping for its restoration from a projected journey to Italy, he died of consumption, June 7, 1826, aged thirty-nine years. His tomb in Munich bears the concise eulogy, *Approximavit sidera*.

Bessel had no sooner made himself acquainted with the exquisite defining powers of the Königsberg heliometer, than he resolved to employ them in an attack upon the now secular problem of star-distances. But it was not until 1837 that he found leisure to pursue the inquiry. In choosing his test-star he adopted a new principle. It had hitherto been assumed that our nearest neighbours in space must be found among the brightest ornaments of our skies. The knowledge of stellar proper motions afforded by the critical comparison of recent with earlier star-places, suggested a different criterion of distance. It is impossible to escape from the conclusion that the apparently swiftest-moving stars are, *on the whole*, also the nearest to us, however numerous the individual exceptions to the rule. Now, as early as 1792,[69] Piazzi had noted as an indication of relative vicinity to the earth, the unusually large proper motion (5·2′ annually) of a double star of the fifth magnitude in the constellation of the Swan. Still more emphatically in 1812[70] Bessel drew the attention of astronomers to the fact, and 61 Cygni became known as the “flying star.” The *seeming* rate of its flight, indeed, is of so leisurely a kind, that in a thousand years it will have shifted its place by less than 3-1/2 lunar diameters, and that a quarter of a million would be required to carry it round the entire circuit of the visible heavens. Nevertheless, it has few rivals in rapidity of movement, the apparent displacement of the vast majority of stars being, by comparison, almost insensible.

This interesting, though inconspicuous object, then, was chosen by Bessel to be put to the question with his heliometer, while Struve made a similar and somewhat earlier trial with the bright gem of the Lyre, whose Arabic title of the “Falling Eagle” survives as a time-worn remnant in “Vega.” Both astronomers agreed to use the “differential” method, for which their instruments and the vicinity to their selected stars of minute, physically detached companions offered special facilities. In the last month of 1838 Bessel made known the result of one year's observations, showing for 61 Cygni a parallax of about a third of a second (0·3136′).[71] He then had his heliometer taken down and repaired, after which he resumed the inquiry, and finally terminated a series of 402 measures in March 1840.[72] The resulting parallax of 0·3483′ (corresponding to a distance about 600,000 times that of the earth from the sun), seemed to be ascertained beyond the possibility of cavil, and is memorable as the first *published* instance of the fathom-line, so industriously thrown into celestial space, having really and indubitably *touched bottom*. It was confirmed in 1842-43 with curious exactness by C. A. F. Peters at Pulkowa; but later researches showed that it required increase to nearly half a second.[73]

Struve's measurements inspired less confidence. They extended over three years (1835-38), but were comparatively few, and were frequently interrupted. The parallax, accordingly, of about a quarter of a second (0·2613′) which he derived from them for α Lyræ, and announced in 1840,[74] has proved considerably too large.[75]

Meanwhile a result of the same kind, but of a more striking character than either Bessel's or Struve's, had been obtained, one might almost say casually, by a different method and in a distant region. Thomas Henderson, originally an attorney's clerk in his native town of Dundee, had become known for his astronomical attainments, and was appointed in 1831 to direct the recently completed observatory at the Cape of Good Hope. He began observing in April, 1832, and, the serious shortcomings of his instrument notwithstanding, executed during the thirteen months of his tenure of office a surprising amount of first-rate work. With a view to correcting the declination of the lustrous double star α Centauri (which ranks after Sirius and Canopus as the third brightest orb in the heavens), he effected a number of successive determinations of its position, and on being informed of its very considerable proper motion (3·6′ annually), he resolved to examine the observations already made for possible traces of parallactic displacement. This was done on his return to Scotland, where he filled the office of Astronomer Royal from 1834 until his premature death in 1844. The result justified his expectations. From the declination measurements made at the Cape and duly reduced, a parallax of about one second of arc clearly emerged (diminished by Gill's and Elkin's observations, 1882-1883, to O·75′); but, by perhaps an excess of caution, was withheld from publication until fuller certainty was afforded by the concurrent testimony of Lieutenant Meadows's determinations of the same star's right ascension.[76] When at last, January 9, 1839, Henderson communicated his discovery to the Astronomical Society, he could no longer claim the priority which was his due. Bessel had anticipated him with the parallax of 61 Cygni by just two months.

Thus from three different quarters, three successful and almost simultaneous assaults were delivered upon a long-beleaguered citadel of celestial secrets. The same work has since been steadily pursued, with the general result of showing that, as regards their overwhelming majority, the stars are far too remote to show even the slightest trace of optical shifting from the revolution of the earth in its orbit. In nearly a hundred cases, however, small parallaxes have been determined, some certainly (that is, within moderate limits of error), others more or less precariously. The list is an instructive one, in its omissions no less than in its contents. It includes stars of many degrees of brightness, from Sirius down to a nameless telescopic star in the Great Bear;[77] yet the vicinity to the earth of this minute object is so much greater than that of the brilliant Vega, that the latter transported to its place would increase in lustre thirty-eight times. Moreover, many of the brightest stars are found to have no sensible parallax, while the majority of those ascertained to be nearest to the earth are of fifth, sixth, even ninth magnitudes. The obvious conclusions follow that the range of variety in the sidereal system is enormously greater than had been supposed, and that estimates of distance based upon apparent magnitude must be wholly futile. Thus, the splendid Canopus, Betelgeux, and Rigel can be inferred, from their indefinite remoteness, to exceed our sun thousands of times in size and lustre; while many inconspicuous objects, which prove to be in our relative vicinity, must be notably his inferiors. The limits of real stellar magnitude are then set very widely apart. At the same time, the so-called "optical" and "geometrical" methods of relatively estimating star-distances are both seen to have a foundation of fact, although so disguised by complicated relations as to be of very doubtful individual application. On the whole, the chances are in favour of the superior vicinity of a bright star over a faint one; and, on the whole, the stars in swiftest *apparent* motion are amongst those whose *actual* remoteness is least. Indeed, there is no escape from either conclusion, unless on the supposition of special arrangements in themselves highly improbable, and, we may confidently say, non-existent.

The distances even of the few stars found to have measurable parallaxes are on a scale entirely beyond the powers of the human mind to conceive. In the attempt both to realize them distinctly, and to express them conveniently, a new unit of length, itself of bewildering magnitude, has originated. This is what we may call the *light-journey* of one year. The subtle vibrations of the ether, propagated on all sides from the surface of luminous bodies, travel at the rate of 186,300 miles a second, or (in round numbers) six billions of miles a year. Four and a third such measures are needed to span the abyss that separates us from the nearest fixed star. In other words, light takes four years and four months to reach the earth from α Centauri; yet α Centauri lies some ten billions of miles nearer to us (so far as is yet known) than any other member of the sidereal system!

The determination of parallax leads, in the case of stars revolving in known orbits, to the determination of mass; for the distance from the earth of the two bodies forming a binary system being ascertained, the seconds of arc apparently separating them from each other can be translated into millions of miles; and we only need to add a knowledge of their period to enable us, by an easy sum in proportion, to find their combined mass in terms of that of the sun. Thus, since—according to Dr. Doberck's elements—the components of α

Centauri revolve round their common centre of gravity at a mean distance nearly 25 times the radius of the earth's orbit, in a period of 88 years, the attractive force of the two together must be just twice the solar. We may gather some idea of their relations by placing in imagination a second luminary like our sun in circulation between the orbits of Neptune and Uranus. But systems of still more majestic proportions are reduced by extreme remoteness to apparent insignificance. A double star of the fourth magnitude in Cassiopeia (Eta), to which a small parallax is ascribed on the authority of O. Struve, appears to be above eight times as massive as the central orb of our world; while a much less conspicuous pair—85 Pegasi—exerts, if the available data can be depended upon, no less than thirteen times the solar gravitating power.

Further, the actual rate of proper motions, so far as regards that part of them which is projected upon the sphere, can be ascertained for stars at known distance. The annual journey, for instance, of 61 Cygni *across the line of sight* amounts to 1,000, and that of α Centauri to 446 millions of miles. A small star, numbered 1,830 in Groombridge's Circumpolar Catalogue, "devours the way" at the rate of at least 150 miles a second—a speed, in Newcomb's opinion, beyond the gravitating power of the entire sidereal system to control; and μ Cassiopeiæ possesses above two-thirds of that surprising velocity; while for both objects, radial movements of just sixty miles a second were disclosed by Professor Campbell's spectroscopic measurements.

Herschel's conclusion as to the advance of the sun among the stars was not admitted as valid by the most eminent of his successors. Bessel maintained that there was absolutely no preponderating evidence in favour of its supposed direction towards a point in the constellation Hercules.[78] Biot, Burckhardt, even Herschel's own son, shared his incredulity. But the appearance of Argelander's prize-essay in 1837[79] changed the aspect of the question. Herschel's first memorable solution in 1783 was based upon the motions of thirteen stars, imperfectly known; his second, in 1805, upon those of no more than six. Argelander now obtained an entirely concordant result from the large number of 390, determined with the scrupulous accuracy characteristic of Bessel's work and his own. The reality of the fact thus persistently disclosed could no longer be doubted; it was confirmed five years later by the younger Struve, and still more strikingly in 1847[80] by Galloway's investigations, founded exclusively on the apparent displacements of southern stars. In 1859 and 1863, Sir George Airy and Mr. Dunkin (1821-1898),[81] employing all the resources of modern science, and commanding the wealth of material furnished by 1,167 proper motions carefully determined by Mr. Main, reached conclusions closely similar to that indicated nearly eighty years previously by the first great sidereal astronomer; which Mr. Plummer's reinvestigation of the subject in 1883[82] served but slightly to modify. Yet astronomers were not satisfied. Dr. Auwers of Berlin completed in 1866 a splendid piece of work, for which he received in 1888 the Gold Medal of the Royal Astronomical Society. It consisted in reducing afresh, with the aid of the most refined modern data, Bradley's original stars, and comparing their places thus obtained for the year 1755 with those assigned to them from observations made at Greenwich after the lapse of ninety years. In the interval, as was to be anticipated, most of them were found to have travelled over some small span of the heavens, and there resulted a stock of nearly three thousand highly authentic proper motions. These ample materials were turned to account by M. Ludwig Struve[83] for a discussion of the sun's motion, of which the upshot was to shift its point of aim to the bordering region of the constellations Hercules and Lyra. And the more easterly position of the solar apex was fully confirmed by the experiments, with variously assorted lists of stars, of Lewis Boss of Albany,[84] and Oscar Stumpe of Bonn.[85] Fresh precautions of refinement were introduced into the treatment of the subject by Ristenpart of Karlsruhe,[86] by Kapteyn of Groningen,[87] by Newcomb[88] and Porter[89] in America, who ably availed themselves of the copious materials accumulated before the close of the century. Their results, although not more closely accordant than those of their predecessors, combined to show that the journey of our system is directed towards a point within a circle about ten degrees in radius, having the brilliant Vega for its centre. To determine its rate was a still more arduous problem. It involved the assumption, very much at discretion, of an average parallax for the stars investigated; and Otto Struve's estimate of 154 million miles as the span yearly traversed was hence wholly unreliable. Fortunately, however, as will be seen further on, a method of determining the sun's velocity independently of any knowledge of star-distances, has now become available.

As might have been expected, speculation has not been idle regarding the purpose and goal of the strange voyage of discovery through space upon which our system is embarked; but altogether fruitlessly. The variety of the conjectures hazarded in the matter is in itself a measure of their futility. Long ago, before the construction of the heavens had as yet been made the subject of methodical inquiry, Kant was disposed to regard Sirius as the "central sun" of the Milky Way; while Lambert surmised that the vast Orion nebula might serve as the regulating power of a subordinate group including our sun. Herschel threw out the hint that the great cluster in Hercules might prove to be the supreme seat of attractive force;[90] Argelander placed his central body in the constellation Perseus;[91] Fomalhaut, the brilliant of the Southern Fish, was set in the post of honour by Boguslawski of Breslau. Mädler (who succeeded Struve at Dorpat in 1839) concluded from a more formal inquiry that the ruling power in the sidereal system resided, not in any single prepondering mass, but in the centre of gravity of the self-controlled revolving multitude.[92] In the former case (as we know from the example of the planetary scheme), the stellar motions would be most rapid near the centre; in the latter, they would become accelerated with remoteness from it.[93] Mädler showed that no part of the heavens could be indicated as a region of exceptionally swift movements, such as would result from the presence of a gigantic (though possibly obscure) ruling body; but that a community of extremely sluggish movements undoubtedly existed in and near the group of the Pleiades, where, accordingly, he placed the centre of gravity of the Milky Way.[94] The bright star Alcyone thus became the "central sun," but in a purely passive sense, its headship being determined by its situation at the point of neutralisation of opposing tendencies, and of consequent rest. By an avowedly conjectural method, the solar period of revolution round this point was fixed at 18,200,000 years.

The scheme of sidereal government framed by the Dorpat astronomer was, it may be observed, of the most approved constitutional type; deprivation, rather than increase of influence accompanying the office of chief dignitary. But while we are still ignorant, and shall perhaps ever remain so, of the fundamental plan upon which the Galaxy is organised, recent investigations tend more and more to exhibit it, not as monarchical (so to speak), but as federative. The community of proper motions detected by Mädler in the vicinity of the Pleiades may accordingly possess a significance altogether different from what he imagined.

Bessel's so-called "foundation of an Astronomy of the Invisible" now claims attention.[95] His prediction regarding the planet Neptune does not belong to the present division of our subject; a strictly analogous discovery in the sidereal system was, however, also very clearly foreshadowed by him. His earliest suspicions of non-uniformity in the proper motion of Sirius dated from 1834; they extended to Procyon in 1840; and after a series of refined measurements with the new Repsold circle, he announced in 1844 his conclusion that these irregularities were due to the presence of obscure bodies round which the two bright Dog-stars revolved as they pursued their way across the sphere.[96] He even assigned to each an approximate period of half a century. "I adhere to the conviction," he wrote later to Humboldt, "that Procyon and Sirius form real binary systems, consisting of a visible and an invisible star. There is no reason to suppose luminosity an essential quality of cosmical bodies. The visibility of countless stars is no argument against the invisibility of countless others."[97]

An inference so contradictory to received ideas obtained little credit, until Peters found, in 1851,[98] that the apparent anomalies in the movements of Sirius could be completely explained by an orbital revolution in a period of fifty years. Bessel's prevision was destined to be still more triumphantly vindicated. On the 31st of January, 1862, while in the act of trying a new 18-inch refractor, Mr. Alvan G. Clark (one of the celebrated firm of American opticians) actually discovered the hypothetical Sirian companion in the precise position required by theory. It has now been watched through nearly an entire revolution (period 49·4 years), and proves to be very slightly luminous in proportion to its mass. Its attractive power, in fact, is nearly half that of its primary, while it emits only 1/10000th of its light. Sirius itself, on the other hand, possesses a far higher radiative intensity than our sun. It gravitates—admitting Sir David Gill's parallax of 0·38′ to be exact—like two suns, but shines like twenty. Possibly it is much distended by heat, and undoubtedly its atmosphere intercepts a very much smaller proportion of its light than in stars of the solar class. As regards Procyon, visual verification was awaited until November 13, 1896, when Professor Schaeberle, with the great Lick refractor, detected the long-sought object in the guise of a thirteenth-magnitude star. Dr. See's calculations[99] showed it to possess one-fifth the mass of its primary, or rather more than half that of our sun.[100] Yet it gives barely 1/20000th of the sun's light, so that it is still nearer to total obscurity than the dusky satellite of Sirius. The period of forty years assigned to the system by Auwers in 1862[101] appears to be singularly exact.

But Bessel was not destined to witness the recognition of "the invisible" as a legitimate and profitable field for astronomical research. He died March 17, 1846, just six months before the discovery of Neptune, of an obscure disease, eventually found to be occasioned by an extensive fungus-growth in the stomach. The place which he left vacant was not one easy to fill. His life's work might be truly described as "epoch-making." Rarely indeed shall we find one who reconciled with the same success the claims of theoretical and practical astronomy, or surveyed the science which he had made his own with a glance equally comprehensive, practical, and profound.

The career of Friedrich Georg Wilhelm Struve illustrates the maxim that science *differentiates* as it develops. He was, while much besides, a specialist in double stars. His earliest recorded use of the telescope was to verify Herschel's conclusion as to the revolving movement of Castor, and he never varied from the predilection which this first observation at once indicated and determined. He was born at Altona, of a respectable yeoman family, April 15, 1793, and in 1811 took a degree in philology at the new Russian University of Dorpat. He then turned to science, was appointed in 1813 to a professorship of astronomy and mathematics, and began regular work in the Dorpat Observatory just erected by Parrot for Alexander I. It was not, however, until 1819 that the acquisition of a 5-foot refractor by Troughton enabled him to take the position-angles of double stars with regularity and tolerable precision. The resulting catalogue of 795 stellar systems gave the signal for a general resumption of the Herschelian labours in this branch. His success, so far, and the extraordinary facilities for observation afforded by the Fraunhofer achromatic encouraged him to undertake, February 11, 1825, a review of the entire heavens down to 15° south of the celestial equator, which occupied more than two years, and yielded, from an examination of above 120,000 stars, a harvest of about 2,200 previously unnoticed composite objects. The ensuing ten years were devoted to delicate and patient measurements, the results of which were embodied in *Mensuræ Micrometricæ*, published at St. Petersburg in 1837. This monumental work gives the places, angles of position, distances, colours, and relative brightness of 3,112 double and multiple stars, all determined with the utmost skill and care. The record is one which gains in value with the process of time, and will for ages serve as a standard of reference by which to detect change or confirm discovery.

It appears from Struve's researches that about one in forty of all stars down to the ninth magnitude is composite, but that the proportion is doubled in the brighter orders.[102] This he attributed to the difficulty of detecting the faint companions of very remote orbs. It was also noticed, both by him and Bessel, that double stars are in general remarkable for large proper motions. Struve's catalogue included no star of which the components were more than 32′ apart, because beyond that distance the chances of merely optical juxtaposition become considerable; but the immense preponderance of extremely close over (as it were) loosely yoked bodies is such as to demonstrate their physical connection, even if no other proof were forthcoming. Many stars previously believed to be single divided under the scrutiny of the Dorpat refractor; while in some cases, one member of a supposed binary system revealed itself as double, thus placing the surprised observer in the unexpected presence of a triple group of suns. Five instances were noted of two pairs lying so close together as to induce a conviction of their mutual dependence;[103] besides which, 124 examples occurred of triple, quadruple, and multiple combinations, the reality of which was open to no reasonable doubt.[104]

It was first pointed out by Bessel that the fact of stars exhibiting a common proper motion might serve as an unfailing test of their real association into systems. This was, accordingly, one of the chief criteria employed by Struve to distinguish true binaries from merely optical couples. On this ground alone, 61 Cygni was admitted to be a genuine double star; and it was shown that, although its components appeared to follow almost strictly rectilinear paths, yet the probability of their forming a connected pair is actually greater than that of the sun rising to-morrow morning.[105] Moreover, this tie of an identical movement was discovered to unite bodies[106] far beyond the range of distance ordinarily separating the members of binary systems, and to prevail so extensively as to lead to the conclusion that single do not outnumber conjoined stars more than twice or thrice.[107]

In 1835 Struve was summoned by the Emperor Nicholas to superintend the erection of a new observatory at Pulkowa, near St. Petersburg, destined for the special cultivation of sidereal astronomy. Boundless resources were placed at his disposal, and the institution created by him was acknowledged to surpass all others of its kind in splendour, efficiency, and completeness. Its chief instrumental glory was a refractor of fifteen inches aperture by Merz and Mahler (Fraunhofer's successors), which left the famous Dorpat telescope far behind, and remained long without a rival. On the completion of this model establishment, August 19, 1839, Struve was installed as its director, and continued to fulfil the important duties of the post with his accustomed vigour until 1858, when illness compelled his virtual resignation in favour of his son Otto Struve, born at Dorpat in 1819. He died November 23, 1864.

An inquiry into the laws of stellar distribution, undertaken during the early years of his residence at Pulkowa, led Struve to confirm in the main the inferences arrived at by Herschel as to the construction of the heavens. According to his view, the appearance known as the Milky Way is produced by a collection of irregularly condensed star-clusters, within which the sun is somewhat eccentrically placed. The nebulous ring which thus integrates the light of countless worlds was supposed by him to be made up of stars scattered over a bent or "broken plane," or to lie in two planes slightly inclined to each other, our system occupying a position near their intersection.[108] He further attempted to show that the limits of this vast assemblage must remain for ever shrouded from human discernment, owing to the gradual extinction of light in its passage through space,[109] and sought to confer upon this celebrated hypothesis a definiteness and certainty far beyond the aspirations of its earlier advocates, Chéseaux and Olbers; but arbitrary assumptions vitiated his reasonings on this, as well as on some other points.[110]

In his special line as a celestial explorer of the most comprehensive type, Sir William Herschel had but one legitimate successor, and that successor was his son. John Frederick William Herschel was born at Slough, March 17, 1792, graduated with the highest honours from St. John's College, Cambridge, in 1813, and entered upon legal studies with a view to being called to the Bar. But his share in an early compact with Peacock and Babbage, "to do their best to leave the world wiser than they found it," was not thus to be fulfilled. The acquaintance of Dr. Wollaston decided his scientific vocation. Already, in 1816, we find him reviewing some of his father's double stars; and he completed in 1820 the 18-inch speculum which was to be the chief instrument of his investigations. Soon afterwards, he undertook, in conjunction with Mr. (later Sir James) South, a series of observations, issuing in the presentation to the Royal Society of a paper[111] containing micrometrical measurements of 380 binary stars, by which the elder Herschel's inferences of orbital motion were, in many cases, strikingly confirmed. A star in the Northern Crown, for instance (η Coronæ), had completed more than one entire circuit since its first discovery; another, τ Ophiuchi, had *closed up* into apparent singleness; while the motion of a third, ξ Ursæ Majoris, in an obviously eccentric orbit, was so rapid as to admit of being traced and measured from month to month.

It was from the first confidently believed that the force retaining double stars in curvilinear paths was identical with that governing the planetary revolutions. But that identity was not ascertained until Savary of Paris showed, in 1827,[112] that the movements of the above-named binary in the Great Bear could be represented with all attainable accuracy by an ellipse calculated on orthodox gravitational principles with a period of 58-1/4 years. Encke followed at Berlin with a still more elegant method; and Sir John Herschel, pointing out the uselessness of analytical refinements where the data were necessarily so imperfect, described in 1832 a graphical process by which "the aid of the eye and hand" was brought in "to guide the judgment in a case where judgment only, and not calculation, could be of any avail."[113] Improved methods of the same kind were published by Dr. See in 1893,[114] and by Mr. Burnham in 1894;[115] and our acquaintance with stellar orbits is steadily gaining precision, certainty, and extent.

In 1825 Herschel undertook, and executed with great assiduity during the ensuing eight years, a general survey of the northern heavens, directed chiefly towards the verification of his father's nebular discoveries. The outcome was a catalogue of 2,306 nebulæ and clusters, of which 525 were observed for the first time, besides 3,347 double stars discovered almost incidentally.[116] "Strongly invited," as he tells us himself, "by the peculiar interest of the subject, and the wonderful nature of the objects which presented themselves," he resolved to attempt the completion of the survey in the southern hemisphere. With this noble object in view, he embarked his family and instruments on board the *Mount Stewart Elphinstone*, and, after a prosperous voyage, landed at Cape Town on the 16th of January, 1834. Choosing as the scene of his observations a rural spot under the shelter of Table Mountain, he began regular "sweeping" on the 5th of March. The site of his great reflector is now marked with an obelisk, and the name of Feldhausen has become memorable in the history of science; for the four years' work done there may truly be said to open the chapter of our knowledge as regards the southern skies.

The full results of Herschel's journey to the Cape were not made public until 1847, when a splendid volume[117] embodying them was brought out at the expense of the Duke of Northumberland. They form a sequel to his father's labours such as the investigations of one man have rarely received from those of another. What the elder observer did for the northern heavens, the younger did for the southern, and with generally concordant results. Reviving the paternal method of "star-gauging," he showed, from a count of 2,299 fields, that the Milky Way surrounds the solar system as a complete annulus of minute stars; not, however, quite symmetrically, since the sun was thought to lie somewhat nearer to those portions visible in the southern hemisphere, which display a brighter lustre and a more complicated structure than the northern branches. The singular cosmical agglomerations known as the "Magellanic Clouds" were now, for the first time, submitted to a detailed, though admittedly incomplete, examination, the almost inconceivable richness and variety of their contents being such that a lifetime might with great profit be devoted to their study. In the Greater Nubecula, within a compass of forty-two square degrees, Herschel reckoned 278 distinct nebulæ and clusters, besides fifty or sixty outliers, and a large number of stars intermixed with diffused nebulosity—in all, 919 catalogued objects, and, for the Lesser Cloud, 244. Yet this was only the most conspicuous part of what his twenty-foot revealed. Such an extraordinary concentration of bodies so various led him to the inevitable conclusion that "the Nubeculæ are to be regarded as systems *sui generis*, and which have no analogues in our hemisphere."[118] He noted also the blankness of surrounding space, especially in the case of Nubecula Minor, "the access to which on all sides," he remarked, "is through a desert;" as if the cosmical material in the neighbourhood had been swept up and garnered in these mighty groups.[119]

Of southern double stars, he discovered and gave careful measurements of 2,102, and described 1,708 nebulæ, of which at least 300 were new. The list was illustrated with a number of drawings, some of them extremely beautiful and elaborate.

Sir John Herschel's views as to the nature of nebulæ were considerably modified by Lord Rosse's success in "resolving" with his great reflectors a crowd of these objects into stars. His former somewhat hesitating belief in the existence of phosphorescent matter, "disseminated through extensive regions of space in the manner of a cloud or fog,"[120] was changed into a conviction that no valid distinction could be established between the faintest wisp of cosmical vapour just discernible in a powerful telescope, and the most brilliant and obvious cluster. He admitted, however, an immense range of possible variety in the size and mode of aggregation of the stellar constituents of various nebulæ. Some might appear nebulous from the closeness of their parts; some from their smallness. Others, he suggested, might be formed of "discrete luminous bodies floating in a non-luminous medium;"[121] while the annular kind probably consisted of "hollow shells of stars."[122] That a physical, and not merely an optical, connection unites nebulæ with the *embroidery* (so to speak) of small stars with which they are in many instances profusely decorated, was evident to him, as it must be to all who look as closely and see as clearly as he did. His description of No. 2,093 in his northern catalogue as "a network or tracery of nebula following the lines of a similar network of stars,"[123] would alone suffice to dispel the idea of accidental scattering; and many other examples of a like import might be quoted. The remarkably frequent occurrence of one or more minute stars in the close vicinity of "planetary" nebulæ led him to infer their dependent condition; and he advised the maintenance of a strict watch for evidences of circulatory movements, not only over these supposed stellar satellites, but also over the numerous "double nebulæ," in which, as he pointed out, "all the varieties of double stars as to distance, position, and relative brightness, have their counterparts." He, moreover, investigated the subject of nebular distribution by the simple and effectual method of graphic delineation or "charting," and succeeded in showing that while a much greater uniformity of scattering prevails in the southern than in the northern heavens, a condensation is nevertheless perceptible about the constellations Pisces and Cetus, roughly corresponding to the "nebular region" in Virgo by its vicinity (within 20° or 30°) to the opposite pole of the Milky Way. He concluded "that the nebulous system is distinct from the sidereal, though involving, and perhaps to a certain extent intermixed with, the latter."[124]

Towards the close of his residence at Feldhausen, Herschel was fortunate enough to witness one of those singular changes in the aspect of the firmament which occasionally challenge the attention even of the incurious, and excite the deepest wonder of the philosophical observer. Immersed apparently in the Argo nebula is a star denominated η Carinæ. When Halley visited St. Helena in 1677, it seemed of the fourth magnitude; but Lacaille in the middle of the following century, and others after him, classed it as of the second. In 1827 the traveller Burchell, being then at St. Paul, near Rio Janeiro, remarked that it had unexpectedly assumed the first rank—a circumstance the more surprising to him because he had frequently, when in Africa during the years 1811 to 1815, noted it as of only fourth magnitude. This observation, however, did not become generally known until later. Herschel, on his arrival at Feldhausen, registered the star as a bright second, and had no suspicion of its unusual character until December 16, 1837, when he suddenly perceived its light to be almost tripled. It then far outshone Rigel in Orion, and on the 2nd of January following it very nearly matched α Centauri. From that date it declined; but a second and even brighter maximum occurred in April, 1843, when Maclear, then director of the Cape Observatory, saw it blaze out with a splendour approaching that of Sirius. Its waxings and wanings were marked by curious "trepidations" of brightness extremely perplexing to theory. In 1863 it had sunk below the fifth magnitude, and in 1869 was barely visible to the naked eye; yet it was not until eighteen years later that it touched a minimum of 7·6 magnitude. Soon afterwards a recovery of brightness set in, but was not carried very far; and the star now shines steadily as of the seventh magnitude, its reddish light contrasting effectively with the silvery rays of the surrounding nebula. An attempt to include its fluctuations within a cycle of seventy years[125] has signally failed; the extent and character of the vicissitudes to which it is subject stamping it rather as a species of connecting link between periodic and temporary stars.[126]

Among the numerous topics which engaged Herschel's attention at the Cape was that of relative stellar brightness. Having contrived an "astrometer" in which an "artificial star," formed by the total reflection of moonlight from the base of a prism, served as a standard of comparison, he was able to estimate the lustre of the *natural* stars examined by the distances at which the artificial object appeared equal respectively to each. He thus constructed a table of 191 of the principal stars,[127] both in the northern and southern hemispheres, setting forth the numerical values of their apparent brightness relatively to that of α Centauri, which he selected as a unit of measurement. Further, the light of the full moon being found by him to exceed that of his standard star 27,408 times, and Dr. Wollaston having shown that the light of the full moon is to that of the sun as 1:801,072[128] (Zöllner made the ratio 1:618,000), it became possible to compare stellar with solar radiance. Hence was derived, in the case of the few stars at ascertained distances, a knowledge of real lustre. Alpha Centauri, for example, emits less than twice, Capella one hundred times as much light as our sun; while Arcturus, at its enormous distance, must display the splendour of 1,300 such luminaries.

Herschel returned to England in the spring of 1838, bringing with him a wealth of observation and discovery such as had perhaps never before been amassed in so short a time. Deserved honours awaited him. He was created a baronet on the occasion of the Queen's coronation (he had been knighted in 1831); universities and learned societies vied with each other in showering distinctions upon him; and the success of an enterprise in which scientific zeal was tinctured with an attractive flavour of adventurous romance, was justly regarded as a matter of national pride. His career as an observing astronomer was now virtually closed, and he devoted his leisure to the collection and arrangement of the abundant trophies of his father's and his own activity. The resulting great catalogue of

5,079 nebulæ (including all then certainly known), published in the *Philosophical Transactions* for 1864, is, and will probably long remain, the fundamental source of information on the subject;[129] but he unfortunately did not live to finish the companion work on double stars, for which he had accumulated a vast store of materials.[130] He died at Collingwood in Kent, May 11, 1871, in the eightieth year of his age, and was buried in Westminster Abbey, close beside the grave of Sir Isaac Newton.

The consideration of Sir John Herschel's Cape observations brings us to the close of the period we are just now engaged in studying. They were given to the world, as already stated, three years before the middle of the century, and accurately represent the condition of sidereal science at that date. Looking back over the fifty years traversed, we can see at a glance how great was the stride made in the interval. Not alone was acquaintance with individual members of the cosmos vastly extended, but their mutual relations, the laws governing their movements, their distances from the earth, masses, and intrinsic lustre, had begun to be successfully investigated. *Begun to be*; for only regarding a scarcely perceptible minority had even approximate conclusions been arrived at. Nevertheless the whole progress of the future lay in that beginning; it was the thin end of the wedge of exact knowledge. The principle of measurement had been substituted for that of probability; a basis had been found large and strong enough to enable calculation to ascend from it to the sidereal heavens; and refinements had been introduced, fruitful in performance, but still more in promise. Thus, rather the kind than the amount of information collected was significant for the time to come—rather the methods employed than the results actually secured rendered the first half of the nineteenth century of epochal importance in the history of our knowledge of the stars.

FOOTNOTES:

[58] Bessel, *Populäre Vorlesungen*, pp. 6, 408.

[59] Fitted to the old transit instrument, July 11, 1772.

[60] *Briefwechsel mit Olbers*, p. xvi.

[61] R. Wolf, *Gesch. der Astron.*, p. 518.

[62] Bessel, *Pop. Vorl.*, p. 22.

[63] A new reduction of the observations upon which they were founded was undertaken in 1896 by Herman S. Davis, of the U.S. Coast Survey.

[64] Bessel, *Pop. Vorl.*, p. 440.

[65] Durège, *Bessel's Leben und Wirken*, p. 28.

[66] *Bonner Beobachtungen*, Bd. iii.-v., 1859-62.

[67] Bessel, *Pop. Vorl.*, p. 238.

[68] The heads of the screws applied to move the halves of the object-glass in the Königsberg heliometer are of so considerable a size that a thousandth part of a revolution, equivalent to 1/20 of a second of arc, can be measured with the utmost accuracy. Main, *R. A. S. Mem.*, vol. xii., p. 53.

[69] *Specola Astronomica di Palermo*, lib. vi., p. 10, *note*.

[70] *Monatliche Correspondenz*, vol. xxvi., p. 162.

[71] *Astronomische Nachrichten*, Nos. 365-366. It should be explained that what is called the “annual parallax” of a star is only half its apparent displacement. In other words, it is the angle subtended at the distance of that particular star by the *radius* of the earth’s orbit.

[72] *Astr. Nach.*, Nos. 401-402.

[73] Sir R. Ball’s measurements at Dunsink gave to 61 Cygni a parallax of 0·47′; Professor Pritchard obtained, by photographic determinations, one of 0·43′.

[74] *Additamentum in Mensuras Micrometricas*, p. 28.

[75] Elkin’s corrected result (in 1897) for the parallax of Vega is 0·082′.

[76] *Mem. Roy. Astr. Soc.*, vol. xi., p. 61.

[77] That numbered 21,185 in Lalande’s *Hist. Cél.*, found by Argelander to have a proper motion of 4·734′, and by Winnecke a parallax of O·511′. *Month. Not.*, vol. xviii., p. 289.

[78] *Fund. Astr.*, p. 309.

[79] *Mém. Prés. à l’Ac. de St. Pétersb.*, t. iii.

[80] *Phil. Trans.*, vol. cxxxvii., p. 79.

[81] *Mem. Roy. Astr. Soc.*, vols. xxviii. and xxxii.

[82] *Ibid.*, vol. xlvii., p. 327.

[83] *Mémoires de St. Pétersbourg*, t. xxxv., No. 3, 1887; revised in *Astr. Nach.*, Nos. 3,729-30, 1901.

[84] *Astronomical Journal*, Nos. 213, 501.

[85] *Astr. Nach.*, Nos. 2,999, 3,000.

[86] *Veröffentlichungen der Grossh. Sternwarte zu Karlsruhe*, Bd. iv., 1892.

[87] *Proceedings Amsterdam Acad. of Sciences*, Jan. 27, 1900.

[88] *Astr. Jour.*, No. 457.

[89] *Ibid.*, Nos. 276, 497.

[90] *Phil. Trans.*, vol. xcvi., p. 230.

[91] *Mém. Prés. à l’Ac. de St. Pétersbourg*, t. iii., p. 603 (read Feb. 5, 1837).

[92] *Die Centralsonne*, *Astr. Nach.*, Nos. 566-567, 1846.

[93] Sir J. Herschel, note to *Treatise on Astronomy*, and *Phil. Trans.*, vol. cxxiii., part ii., p. 502.

[94] The position is (as Sir J. Herschel pointed out, *Outlines of Astronomy*, p. 631, 10th ed.) placed beyond the range of reasonable probability by its remoteness (fully 26°) from the galactic plane.

[95] Mädler in *Westermann’s Jahrbuch*, 1867, p. 615.

[96] Letter from Bessel to Sir J. Herschel, *Month. Not.*, vol. vi., p. 139.

[97] Wolf, *Gesch. d. Astr.*, p. 743, *note*.

[98] *Astr. Nach.*, Nos. 745-748.

[99] *Astr. Jour.*, No. 440.

[100] Adopting Elkin’s revised parallax for Procyon of 0·325′.

[101] *Astr. Nach.*, Nos. 1371-1373.

[102] *Ueber die Doppelsterne*, Bericht, 1827, p. 22.

[103] *Ueber die Doppelsterne*, Bericht, 1827, p. 25.

[104] *Mensuræ Micr.*, p. xcix.

[105] *Stellarum Fixarum imprimis Duplicium et Multiplicum Positiones Mediæ*, pp. cxc., cciii.

[106] For instance, the southern stars, 36A Ophiuchi (itself double) and 30 Scorpii, which are 12′ 10″ apart. *Ibid.*, p. cciii.

[107] *Stellarum Fixarum*, etc., p. ccliii.

[108] *Études d'Astronomie Stellaire*, 1847, p. 82.

[109] *Ibid.*, p. 86.

[110] See Encke's criticism in *Astr. Nach.*, No. 622.

[111] *Phil. Trans.*, vol. cxiv., part iii., 1824.

[112] *Conn. d. Temps*, 1830.

[113] *R. A. S. Mem.*, vol. v., p. 178, 1833.

[114] *Astr. and Astrophysics*, vol. xii., p. 581.

[115] *Popular Astr.*, vol. i., p. 243.

[116] *Phil. Trans.*, vol. cxxiii., and *Results*, etc., Introd.

[117] *Results of Astronomical Observations made during the years 1834-8 at the Cape of Good Hope.*

[118] *Results*, etc., p. 147.

[119] See Proctor's *Universe of Stars*, p. 92.

[120] *A Treatise on Astronomy*, 1833, p. 406.

[121] *Results*, etc., p. 139.

[122] *Ibid.*, pp. 24, 142.

[123] *Phil. Trans.*, vol. cxxiii., p. 503.

[124] *Results*, etc., p. 136.

[125] Loomis, *Month. Not.*, vol. xxix., p. 298.

[126] See the Author's *System of the Stars*, pp. 116-120.

[127] *Outlines of Astr.*, App. I.

[128] *Phil. Trans.*, vol. cxix., p. 27.

[129] Dr. Dreyer's New General Catalogue, published in 1888 as vol. xlix. of the Royal Astronomical Society's *Memoirs*, is an enlargement of Herschel's work. It includes 7,840 entries, and was supplemented, in 1895, by an "Index Catalogue" of 1,529 nebulæ discovered 1888 to 1894. *Mem. R. A. S.*, vol. li.

[130] A list of 10,320 composite stars was drawn out by him in order of right ascension, and has been published in vol. xl. of *Mem. R. A. S.*; but the data requisite for their formation into a catalogue were not forthcoming. See Main's and Pritchard's *Preface* to above, and Dunkin's *Obituary Notices*, p. 73.

CHAPTER III

PROGRESS OF KNOWLEDGE REGARDING THE SUN

The discovery of sun-spots in 1610 by Fabricius and Galileo first opened a way for inquiry into the solar constitution; but it was long before that way was followed with system or profit. The seeming irregularity of the phenomena discouraged continuous attention; casual observations were made the basis of arbitrary conjectures, and real knowledge received little or no increase. In 1620 we find Jean Tarde, Canon of Sarlat, arguing that because the sun is "the eye of the world," and the eye of the world *cannot suffer from ophthalmia*, therefore the appearances in question must be due, not to actual specks or stains on the bright solar disc, but to the transits of a number of small planets across it! To this new group of heavenly bodies he gave the name of "Borbonia Sidera," and they were claimed in 1633 for the House of Hapsburg, under the title of "Austriaca Sidera" by Father Malapertius, a Belgian Jesuit.[131] A similar view was temporarily maintained against Galileo by the justly celebrated Father Scheiner of Ingolstadt, and later by William Gascoigne, the inventor of the micrometer; but most of those who were capable of thinking at all on such subjects (and they were but few) adhered either to the *cloud theory* or to the *slag theory* of sun-spots. The first was championed by Galileo, the second by Simon Marius, "astronomer and physician" to the brother Margraves of Brandenburg. The latter opinion received a further notable development from the fact that in 1618, a year remarkable for the appearance of three bright comets, the sun was almost free from spots; whence it was inferred that the cindery refuse from the great solar conflagration, which usually appeared as dark blotches on its surface, was occasionally thrown off in the form of comets, leaving the sun, like a snuffed taper, to blaze with renewed brilliancy.[132]

In the following century, Derham gathered from observations carried on during the years 1703-11, "That the spots on the sun are caused by the eruption of some new volcano therein, which at first pouring out a prodigious quantity of smoke and other opacous matter, causeth the spots; and as that fuliginous matter decayeth and spendeth itself, and the volcano at last becomes more torrid and flaming, so the spots decay, and grow to umbræ, and at last to faculæ."[133]

The view, confidently upheld by Lalande,[134] that spots were rocky elevations uncovered by the casual ebbing of a luminous ocean, the surrounding penumbræ representing shoals or sandbanks, had even less to recommend it than Derham's volcanic theory. Both were, however, significant of a growing tendency to bring solar phenomena within the compass of terrestrial analogies.

For 164 years, then, after Galileo first levelled his telescope at the setting sun, next to nothing was learned as to its nature; and the facts immediately ascertained, of its rotation on an axis nearly erect to the plane of the ecliptic, in a period of between twenty-five and twenty-six days, and of the virtual limitation of the spots to a so-called "royal" zone extending some thirty degrees north and south of the solar equator, gained little either in precision or development from five generations of astronomers.

But in November, 1769, a spot of extraordinary size engaged the attention of Alexander Wilson, professor of astronomy in the University of Glasgow. He watched it day by day, and to good purpose. As the great globe slowly revolved, carrying the spot towards its western edge, he was struck with the gradual contraction and final disappearance of the penumbra *on the side next the centre of the disc*; and when on the 6th of December the same spot re-emerged on the eastern limb, he perceived, as he had anticipated, that the shady zone was now deficient *on the opposite side*, and resumed its original completeness as it returned to a central position. In other spots subsequently examined by him, similar perspective effects were visible, and he proved in 1774,[135] by strict geometrical reasoning, that they could only arise in vast photospheric excavations. It was not, indeed, the first time that such a view had been suggested. Father Scheiner's later observations plainly foreshadowed it;[136] a conjecture to the same effect was emitted by Leonard Rost of Nuremburg early in the eighteenth century;[137] both by Lahire in 1703 and by J. Cassini in 1719 spots had been seen as notches on the solar limb; while in 1770 Pastor Schülen of Essingen, from the careful study of phenomena similar to those noted by Wilson, concluded their depressed nature.[138] Modern observations, nevertheless, prove those phenomena to be by no means universally present.

Wilson's general theory of the sun was avowedly tentative. It took the modest form of an interrogatory. "Is it not reasonable to think," he asks, "that the great and stupendous body of the sun is made up of two kinds of matter, very different in their qualities; that by far the greater part is solid and dark, and that this immense and dark globe is encompassed with a thin covering of that resplendent substance from which the sun would seem to derive the whole of his vivifying heat and energy?"[139] He further suggests that the excavations or spots may be occasioned "by the working of some sort of elastic vapour which is generated within the dark globe," and that the luminous matter, being in some degree fluid, and being acted upon by gravity, tends to flow down and cover the nucleus. From these hints, supplemented by his own diligent observations and sagacious reasonings, Herschel elaborated a scheme of solar constitution which held its ground until the physics of the sun were revolutionised by the spectroscope.

A cool, dark, solid globe, its surface diversified with mountains and valleys, clothed in luxuriant vegetation, and "richly stored with inhabitants," protected by a heavy cloud-canopy from the intolerable glare of the upper luminous region, where the dazzling coruscations of a solar aurora some thousands of miles in depth evolved the stores of light and heat which vivify our world—such was the central luminary which Herschel constructed with his wonted ingenuity, and described with his wonted eloquence.

"This way of considering the sun and its atmosphere," he says,[140] "removes the great dissimilarity we have hitherto been used to find between its condition and that of the rest of the great bodies of the solar system. The sun, viewed in this light, appears to be nothing else than a very eminent, large, and lucid planet, evidently the first, or, in strictness of speaking, the only primary one of our system; all others being truly secondary to it. Its similarity to the other globes of the solar system with regard to its solidity, its atmosphere, and its diversified surface, the rotation upon its axis, and the fall of heavy bodies, leads us on to suppose that it is most probably also inhabited, like the rest of the planets, by beings whose organs are adapted to the peculiar circumstances of that vast globe."

We smile at conclusions which our present knowledge condemns as extravagant and impossible, but such incidental flights of fancy in no way derogate from the high value of Herschel's contributions to solar science. The cloud-like character which he attributed to the radiant shell of the sun (first named by Schröter the "photosphere") is borne out by all recent investigations; he observed its mottled or corrugated aspect, resembling, as he described it, the roughness on the rind of an orange; showed that "faculæ" are elevations or heaped-up ridges of the disturbed photospheric matter; and threw out the idea that spots may ensue from an excess of the ordinary luminous emissions. A certain "empyreal" gas was, he supposed (very much as Wilson had done), generated in the body of the sun, and rising everywhere by reason of its lightness, made for itself, when in moderate quantities, small openings or "pores,"[141] abundantly visible as dark points on the solar disc. But should an uncommon quantity be formed, "it will," he maintained, "burst through the planetary[142] regions of clouds, and thus will produce great openings; then, spreading itself above them, it will occasion large shallows (penumbræ), and mixing afterwards gradually with other superior gases, it will promote the increase, and assist in the maintenance, of the general luminous phenomena."[143]

This partial anticipation of the modern view that the solar radiations are maintained by some process of circulation within the solar mass, was reached by Herschel through prolonged study of the phenomena in question. The novel and important idea contained in it, however, it was at that time premature to attempt to develop. But though many of the subtler suggestions of Herschel's genius passed unnoticed by his contemporaries, the main result of his solar researches was an unmistakable one. It was nothing less than the definitive introduction into astronomy of the paradoxical conception of the central fire and hearth of our system as a cold, dark, terrestrial mass, wrapt in a mantle of innocuous radiance—an earth, so to speak, within—a sun without.

Let us pause for a moment to consider the value of this remarkable innovation. It certainly was not a step in the direction of truth. On the contrary, the crude notions of Anaxagoras and Xeno approached more nearly to what we now know of the sun, than the complicated structure devised for the happiness of a nobler race of beings than our own by the benevolence of eighteenth-century astronomers. And yet it undoubtedly constituted a very important advance in science. It was the first earnest attempt to bring solar phenomena within the compass of a rational system; to put together into a consistent whole the facts ascertained; to fabricate, in short, a solar machine that would in some fashion work. It is true that the materials were inadequate and the design faulty. The resulting construction has not proved strong enough to stand the wear and tear of time and discovery, but has had to be taken to pieces and remodelled on a totally different plan. But the work was not therefore done in vain. None of Bacon's aphorisms show a clearer insight into the relations between the human mind and the external world than that which declares "Truth to emerge sooner from error than from confusion."[144] A definite theory (even if a false one) gives holding-ground to thought. Facts acquire a meaning with reference to it. It affords a motive for accumulating them and a means of co-ordinating them; it provides a framework for their arrangement, and a receptacle for their preservation, until they become too strong and numerous to be any longer included within arbitrary limits, and shatter the vessel originally framed to contain them.

Such was the purpose subserved by Herschel's theory of the sun. It helped to *clarify* ideas on the subject. The turbid sense of groping and viewless ignorance gave place to the lucidity of a possible scheme. The persuasion of knowledge is a keen incentive to its increase. Few men care to investigate what they are obliged to admit themselves entirely ignorant of; but once started on the road of knowledge, real or supposed, they are eager to pursue it. By the promulgation of a confident and consistent view regarding the nature of the sun, accordingly, research was encouraged, because it was rendered hopeful, and inquirers were shown a path leading indefinitely onwards where an impassable thicket had before seemed to bar the way.

We have called the "terrestrial" theory of the sun's nature an innovation, and so, as far as its general acceptance is concerned, it may justly be termed; but, like all successful innovations, it was a long time brewing. It is extremely curious to find that Herschel had a predecessor in its advocacy who never looked through a telescope (nor, indeed, imagined the possibility of such an instrument), who knew nothing of sun-spots, was still (mistaken assertions to the contrary notwithstanding) in the bondage of the geocentric system, and regarded nature from the lofty standpoint of an idealist philosophy. This was the learned and enlightened Cardinal Cusa, a fisherman's son from the banks of the Moselle, whose distinguished career in the Church and in literature extended over a considerable part of the fifteenth century (1401-64). In his singular treatise *De Doctâ Ignorantiâ*, one of the most notable literary monuments of the early Renaissance, the following passage occurs:—"To a spectator on the surface of the sun, the splendour which appears to us would be invisible, since it contains, as it were, an earth for its central mass, with a circumferential envelope of light and heat, and between the two an atmosphere of water and clouds and translucent air." The luminary of Herschel's fancy could scarcely be more clearly portrayed; some added words, however, betray the origin of the Cardinal's idea. "The earth also," he says, "would appear as a shining star to any one outside the fiery element." It was, in fact, an extension to the sun of the ancient elemental doctrine; but an extension remarkable at that period, as premonitory of the tendency, so powerfully developed by subsequent discoveries, to assimilate the orbs of heaven to the model of our insignificant planet, and to extend the brotherhood of our system and our species to the farthest limit of the visible or imaginable universe.

In later times we find Flamsteed communicating to Newton, March 7, 1681, his opinion "that the substance of the sun is terrestrial matter, his light but the liquid menstruum encompassing him."[145] Bode in 1776 arrived independently at the conclusion that "the sun is neither burning nor glowing, but in its essence a dark planetary body, composed like our earth of land and water, varied by mountains and valleys, and enveloped in a vaporous atmosphere";[146] and the learned in general applauded and acquiesced. The view, however, was in 1787 still so far from popular, that the holding of it was alleged as a proof of insanity in Dr. Elliot when accused of a murderous assault on Miss Boydell. His friend Dr. Simmons stated on his behalf that he had received from him in the preceding January a letter giving evidence of a deranged mind, wherein he asserted "that the sun is not a body of fire, as hath been hitherto supposed, but that its light proceeds from a dense and universal aurora, which may afford ample light to the inhabitants of the surface beneath, and yet be at such a distance aloft as not to annoy them. No objection, he saith, ariseth to that great luminary's being inhabited; vegetation may obtain there as well as with us. There may be water and dry land, hills and dales, rain and fair weather; and as the light, so the season must be eternal, consequently it may easily be conceived to be by far the most blissful habitation of the whole system!" The Recorder, nevertheless, objected that if an extravagant hypothesis were to be adduced as proof of insanity, the same might hold good with regard to some other speculators, and desired Dr. Simmons to tell the court what he thought of the theories of Burnet and Buffon.[147]

Eight years later, this same "extravagant hypothesis," backed by the powerful recommendation of Sir William Herschel, obtained admittance to the venerable halls of science, there to abide undisturbed for nearly seven decades. Individual objectors, it is true, made themselves heard, but their arguments had little effect on the general body of opinion. Ruder blows were required to shatter an hypothesis flattering to human pride of invention in its completeness, in the plausible detail of observations by which it seemed to be supported, and in its condescension to the natural pleasure in discovering resemblance under all but total dissimilarity.

Sir John Herschel included among the results of his multifarious labours at the Cape of Good Hope a careful study of the sun-spots conspicuously visible towards the end of the year 1836 and in the early part of 1837. They were remarkable, he tells us, for their forms and arrangement, as well as for their number and size; one group, measured on the 29th of March in the latter year, covering (apart from what may be called its outlying dependencies) the vast area of five square minutes or 3,780 million square miles.[148] We have at present to consider, however, not so much these observations in themselves, as the chain of theoretical suggestions by which they were connected. The distribution of spots, it was pointed out, on two zones parallel to the equator, showed plainly their intimate connection with the solar rotation, and indicated as their cause fluid circulations analogous to those producing the terrestrial trade and anti-trade winds.

“The spots, in this view of the subject,” he went on to say,[149] “would come to be assimilated to those regions on the earth’s surface where, for the moment, hurricanes and tornadoes prevail; the upper stratum being temporarily carried downwards, displacing by its impetus the two strata of luminous matter beneath, the upper of course to a greater extent than the lower, and thus wholly or partially denuding the opaque surface of the sun below. Such processes cannot be unaccompanied by vorticose motions, which, left to themselves, die away by degrees and dissipate, with the peculiarity that their lower portions come to rest more speedily than their upper, by reason of the greater resistance below, as well as the remoteness from the point of action, which lies in a higher region, so that their centres (as seen in our waterspouts, which are nothing but small tornadoes) appear to retreat upwards. Now this agrees perfectly with what is observed during the obliteration of the solar spots, which appear as if filled in by the collapse of their sides, the penumbra closing in upon the spot and disappearing after it.”

But when it comes to be asked whether a cause can be found by which a diversity of solar temperature might be produced corresponding with that which sets the currents of the terrestrial atmosphere in motion, we are forced to reply that we know of no such cause. For Sir John Herschel’s hypothesis of an increased retention of heat at the sun’s equator, due to the slightly spheroidal or bulging form of its outer atmospheric envelope, assuredly gives no sufficient account of such circulatory movements as he supposed to exist. Nevertheless, the view that the sun’s rotation is intimately connected with the formation of spots is so obviously correct, that we can only wonder it was not thought of sooner, while we are even now unable to explain with any certainty *how* it is so connected.

Mere scrutiny of the solar surface, however, is not the only means of solar observation. We have a satellite, and that satellite from time to time acts most opportunely as a screen, cutting off a part or the whole of those dazzling rays in which the master-orb of our system veils himself from over-curious regards. The importance of eclipses to the study of the solar surroundings is of comparatively recent recognition; nevertheless, much of what we know concerning them has been snatched, as it were, by surprise under favour of the moon. In former times, the sole astronomical use of such incidents was the correction of the received theories of the solar and lunar movements; the precise time of their occurrence was the main fact to be noted, and subsidiary phenomena received but casual attention. Now, their significance as a geometrical test of tabular accuracy is altogether overshadowed by the interest attaching to the physical observations for which they afford propitious occasions. This change may be said to date, in its pronounced form, from the great eclipse of 1842. Although a necessary consequence of the general direction taken by scientific progress, it remains associated in a special manner with the name of Francis

Baily.

The "philosopher of Newbury" was by profession a London stockbroker, and a highly successful one. Nevertheless, his services to science were numerous and invaluable, though not of the brilliant kind which attract popular notice. Born at Newbury in Berkshire, April 28, 1774, and placed in the City at the age of fourteen, he derived from the acquaintance of Dr. Priestley a love of science which never afterwards left him. It was, however, no passion such as flames up in the brain of the destined discoverer, but a regulated inclination, kept well within the bounds of an actively pursued commercial career. After travelling for a year or two in what were then the wilds of North America, he went on the Stock Exchange in 1799, and earned during twenty-four years of assiduous application to affairs a high reputation for integrity and ability, to which corresponded an ample fortune. In the meantime the Astronomical Society (largely through his co-operation) had been founded; he had for three years acted as its secretary, and he now felt entitled to devote himself exclusively to a subject which had long occupied his leisure hours. He accordingly in 1825 retired from business, purchased a house in Tavistock Place, and fitted up there a small observatory. He was, however, by preference a computator rather than an observer. What Sir John Herschel calls the "archæology of practical astronomy" found in him an especially zealous student. He re-edited the star-catalogues of Ptolemy, Ulugh Beigh, Tycho Brahe, Hevelius, Halley, Flamsteed, Lacaille, and Mayer; calculated the eclipse of Thales and the eclipse of Agathocles, and vindicated the memory of the first Astronomer Royal. But he was no less active in meeting present needs than in revising past performances. The subject of the reduction of observations, then, as we have already explained,[150] in a state of deplorable confusion, attracted his most earnest attention, and he was close on the track of Bessel when made acquainted with the method of simplification devised at Königsberg. Anticipated as an inventor, he could still be of eminent use as a promoter of these valuable improvements; and, carrying them out on a large scale in the star-catalogue of the Astronomical Society (published in 1827), "he put" (in the words of Herschel) "the astronomical world in possession of a power which may be said, without exaggeration, to have changed the face of sidereal astronomy."[151]

His reputation was still further enhanced by his renewal, with vastly improved apparatus, of the method, first used by Henry Cavendish in 1797-98, for determining the density of the earth. From a series of no less than 2,153 delicate and difficult experiments, conducted at Tavistock Place during the years 1838-42, he concluded our planet to weigh 5·66 as much as a globe of water of the same bulk; and this result slightly corrected is still accepted as a very close approximation of the truth.

What we have thus glanced at is but a fragment of the truly surprising mass of work accomplished by Baily in the course of a variously occupied life. A rare combination of qualities fitted him for his task. Unvarying health, undisturbed equanimity, methodical habits, the power of directed and sustained thought, combined to form in him an intellectual toiler of the surest, though not perhaps of the highest quality. He was in harness almost to the end. He was destined scarcely to know the miseries of enforced idleness or of consciously failing powers. In 1842 he completed the laborious reduction of Lalande's great catalogue, undertaken at the request of the British Association, and was still engaged in seeing it through the press when he was attacked with what proved his last, as it was probably his first serious illness. He, however, recovered sufficiently to attend the Oxford Commemoration of July 2, 1844, where an honorary degree of D.C.L. was conferred upon him in company with Airy and Struve; but sank rapidly after the effort, and died on the 30th of August following, at the age of seventy, lamented and esteemed by all who knew him.

It is now time to consider his share in the promotion of solar research. Eclipses of the sun, both ancient and modern, were a speciality with him, and he was fortunate in those which came under his observation. Such phenomena are of three kinds—partial, annular, and total. In a partial eclipse, the moon, instead of passing directly between us and the sun, slips by, as it were, a little on one side, thus cutting off from our sight only a portion of his surface. An annular eclipse, on the other hand, takes place when the moon is indeed centrally interposed, but falls short of the apparent size required for the entire concealment of the solar disc, which consequently remains visible as a bright ring or annulus, even when the obscuration is at its height. In a total eclipse, on the contrary, the sun completely disappears behind the dark body of the moon. The difference of the two latter varieties is due to the fact that the apparent diameter of the sun and moon are so nearly equal as to gain alternate preponderance one over the other through the slight periodical changes in their respective distances from the earth.

Now, on the 15th of May, 1836, an annular eclipse was visible in the northern parts of Great Britain, and was observed by Baily at Inch Bonney, near Jedburgh. It was here that he saw the phenomenon which obtained the name of "Baily's Beads," from the notoriety conferred upon it by his vivid description.

"When the cusps of the sun," he writes, "were about 40° asunder, a row of lucid points, like a string of bright beads, irregular in size and distance from each other, *suddenly* formed round that part of the circumference of the moon that was about to enter on the sun's disc. Its formation, indeed, was so rapid that it presented the appearance of having been caused by the ignition of a fine train of gunpowder. Finally, as the moon pursued her course, the dark intervening spaces (which, at their origin, had the appearance of lunar mountains in high relief, and which still continued attached to the sun's border) were stretched out into long, black, thick, parallel lines, joining the limbs of the sun and moon; when all at once they *suddenly* gave way, and left the circumference of the sun and moon in those points, as in the rest, comparatively smooth and circular, and the moon perceptibly advanced on the face of the sun."[152]

These curious appearances were not an absolute novelty. Weber in 1791, and Von Zach in 1820, had seen the "beads"; Van Swinden had described the "belts" or "threads."[153] These last were, moreover (as Baily clearly perceived), completely analogous to the "black ligament" which formed so troublesome a feature in the transits of Venus in 1764 and 1769, and which, to the regret and confusion, though no longer to the surprise of observers, was renewed in that of 1874. The phenomenon is largely an effect of what is called *irradiation*, by which a bright object seems to encroach upon a dark one; but under good atmospheric and instrumental conditions it becomes inconspicuous. The "Beads" must always appear when the projected lunar edge is serrated with mountains. In Baily's observation, they were exaggerated and distorted by an irradiative *clinging together* of the limbs of sun and moon.

The immediate result, however, was powerfully to stimulate attention to solar eclipses in their *physical* aspect. Never before had an occurrence of the kind been expected so eagerly or prepared for so actively as that which was total over Central and Southern Europe on the 8th of July, 1842. Astronomers hastened from all quarters to the favoured region. The Astronomer Royal (Airy) repaired to Turin; Baily to Pavia; Otto Struve threw aside his work amidst the stars at Pulkowa, and went south as far as Lipeszk; Schumacher travelled from Altona to Vienna; Arago from Paris to Perpignan. Nor did their trouble go unrewarded. The expectations of the most sanguine were outdone by the wonders disclosed.

Baily (to whose narrative we again have recourse) had set up his Dollond's achromatic in an upper room of the University of Pavia, and was eagerly engaged in noting a partial repetition of the singular appearances seen by him in 1836, when he was "astounded by a tremendous burst of applause from the streets below, and at the same moment was electrified at the sight of one of the most brilliant and splendid phenomena that can well be imagined. For at that instant the dark body of the moon was suddenly surrounded with a corona, or kind of bright glory similar in shape and relative magnitude to that which painters draw round the heads of saints, and which by the French is designated an *auréole*. Pavia contains many thousand inhabitants, the major part of whom were, at this early hour, walking about the streets and squares or looking out of windows, in order to witness this long-talked-of phenomenon; and when the total obscuration took place, which was *instantaneous*, there was a universal shout from every observer, which 'made the welkin ring,' and, for the moment, withdrew my attention from the object with which I was immediately occupied. I had indeed anticipated the appearance of a luminous circle round the moon during the time of total obscurity; but I did not expect, from any of the accounts of preceding eclipses that I had read, to witness so magnificent an exhibition as that which took place…. The breadth of the corona, measured from the circumference of the moon, appeared to me to be nearly equal to half the moon's diameter. It had the appearance of brilliant rays. The light was most dense close to the border of the moon, and became gradually and uniformly more attenuate as its distance therefrom increased, assuming the form of diverging rays in a rectilinear line, which at the extremity were more divided, and of an unequal length; so that in no part of the corona could I discover the regular and well-defined shape of a ring at its *outer* margin. It appeared to me to have the sun for its centre, but I had no means of taking any accurate measures for determining this point. Its colour was quite white, not pearl-colour, nor yellow, nor red, and the rays had a vivid and flickering appearance, somewhat like that which a gaslight illumination might be supposed to assume if formed into a similar shape…. Splendid and astonishing, however, as this remarkable phenomenon really was, and although it could not fail to call forth the admiration and applause of every beholder, yet I must confess that there was at the same time something in its singular and wonderful appearance that was appalling; and I can readily imagine that uncivilised nations may occasionally have become alarmed and terrified at such an object, more especially at times when the true cause of the occurrence may have been but faintly understood, and the phenomenon itself wholly unexpected.

"But the most remarkable circumstance attending the phenomenon was the appearance of *three large protuberances* apparently emanating from the circumference of the moon, but evidently forming a portion of the corona. They had the appearance of mountains of a prodigious elevation; their colour was red, tinged with lilac or purple; perhaps the colour of the peach-blossom would more nearly represent it. They somewhat resembled the snowy tops of the Alpine mountains when coloured by the rising or setting sun. They resembled the Alpine mountains also in another respect, inasmuch as their light was perfectly steady, and had none of that flickering or sparkling motion so visible in other parts of the corona. All the three projections were of the same roseate cast of colour, and very different from the brilliant vivid white light that formed the corona; but they differed from each other in magnitude…. The whole of these three protuberances were visible even to the last moment of total obscuration; at least, I never lost sight of them when looking in that direction; and when the first ray of light was admitted from the sun, they vanished, with the corona, altogether, and daylight was instantaneously restored."[154]

Notwithstanding unfavourable weather, the "red flames" were perceived with little less clearness and no less amazement from the Superga than at Pavia, and were even discerned by Mr. Airy with the naked eye. "Their form" (the Astronomer Royal wrote) "was nearly that of saw-teeth in the position proper for a circular saw turned round in the same direction in which the hands of a watch turn…. Their colour was a full lake-red, and their brilliancy greater than that of any other part of the ring."[155]

The height of these extraordinary objects was estimated by Arago at two minutes of arc, representing, at the sun's distance, an actual elevation of 54,000 miles. When carefully watched, the rose-flush of their illumination was perceived to fade through violet to white as the light returned, the same changes in a reversed order having accompanied their first appearance. Their forms, however, during about three minutes of visibility, showed no change, although of so apparently unstable a character as to suggest to Arago "mountains on the point of crumbling into ruins” through topheaviness.[156]

The corona, both as to figure and extent, presented very different appearances at different stations. This was no doubt due to varieties in atmospheric conditions. At the Superga, for instance, all details of structure seem to have been effaced by the murky air, only a comparatively feeble ring of light being seen to encircle the moon. Elsewhere, a brilliant radiated formation was conspicuous, spreading at four opposite points into four vast luminous expansions, compared to feather-plumes or *aigrettes*.[157] Arago at Perpignan noticed considerable irregularities in the divergent rays. Some appeared curved and twisted, a few lay *across* the others, in a direction almost tangential to the moon’s limb, the general effect being described as that of a “hank of thread in disorder.”[158] At Lipeszk, where the sun stood much higher above the horizon than in Italy or France, the corona showed with surprising splendour. Its apparent extent was judged by Struve to be no less than twenty-five minutes (more than six times Airy’s estimate), while the great plumes spread their radiance to three or four degrees from the dark lunar edge. So dazzling was the light that many well-instructed persons denied the totality of the eclipse. Nor was the error without precedent, although the appearances attending respectively a total and an annular eclipse are in reality wholly dissimilar. In the latter case, the surviving ring of sunlight becomes so much enlarged by irradiation, that the interposed dark lunar body is reduced to comparative insignificance, or even invisibility. Maclaurin tells us[159] that during an eclipse of this character which he observed at Edinburgh in 1737, “gentlemen by no means shortsighted declared themselves unable to discern the moon upon the sun without the aid of a smoked glass;” and Baily (who, however, *was* shortsighted) could distinguish, in 1836, with the naked eye, no trace of “the globe of purple velvet” which the telescope revealed as projected upon the face of the sun.[160] Moreover, the diminution of light is described by him as “little more than might be caused by a temporary cloud passing over the sun”; the birds continued in full song, and “one cock in particular was crowing with all his might while the annulus was forming.”

Very different were the effects of the eclipse of 1842, as to which some interesting particulars were collected by Arago.[161] Beasts of burthen, he tells us, paused in their labour, and could by no amount of punishment be induced to move until the sun reappeared. Birds and beasts abandoned their food; linnets were found dead in their cages; even ants suspended their toil. Diligence-horses, on the other hand, seemed as insensible to the phenomenon as locomotives. The convolvulus and some other plants closed their leaves, but those of the mimosa remained open. The little light that remained was of a livid hue. One observer described the general coloration as resembling the lees of wine, but human faces showed pale olive or greenish. We may, then, rest assured that none of the remarkable obscurations recorded in history were due to eclipses of the annular kind.

The existence of the corona is no modern discovery. Indeed, it is too conspicuous an apparition to escape notice from the least attentive or least practised observer of a total eclipse. Nevertheless, explicit references to it are rare in early times. Plutarch, however, speaks of a "certain splendour" compassing round the hidden edge of the sun, as a regular feature of total eclipses;[162] and the corona is expressly mentioned in a description of an eclipse visible at Corfu in 968 A.D.[163] The first to take the phenomenon into scientific consideration was Kepler. He showed, from the orbital positions at the time of the sun and moon, that an eclipse observed by Clavius at Rome in 1567 could not have been annular,[164] as the dazzling coronal radiance visible during the obscuration had caused it to be believed. Although he himself never witnessed a total eclipse of the sun, he carefully collected and compared the remarks of those more fortunate, and concluded that the ring of "flame-like splendour" seen on such occasions was caused by the reflection of the solar rays from matter condensed in the neighbourhood either of the sun or moon.[165] To the solar explanation he gave his own decided preference; but, with one of those curious flashes of half-prophetic insight characteristic of his genius, declared that "it should be laid by ready for use, not brought into immediate requisition."[166] So literally was his advice acted upon, that the theory, which we now know to be (broadly speaking) the correct one, only emerged from the repository of anticipated truths after 236 years of almost complete retirement, and even then timorously and with hesitation.

The first eclipse of which the attendant phenomena were observed with tolerable exactness was that which was central in the South of France, May 12, 1706. Cassini then put forward the view that the "crown of pale light" seen round the lunar disc was caused by the illumination of the zodiacal light;[167] but it failed to receive the attention which, as a step in the right direction, it undoubtedly merited. Nine years later we meet with Halley's comments on a similar event, the first which had occurred in London since March 20, 1140. By nine in the morning of May 3, 1715, the obscuration, he tells us, "was about ten digits,[168] when the face and colour of the sky began to change from perfect serene azure blue to a more dusky livid colour, having an eye of purple intermixt…. A few seconds before the sun was all hid, there discovered itself round the moon a luminous ring, about a digit or perhaps a tenth part of the moon's diameter in breadth. It was of a pale whiteness, or rather pearl colour, seeming to be a little tinged with the colours of the iris, and to be concentric with the moon, whence I concluded it the moon's atmosphere. But the great height thereof, far exceeding our earth's atmosphere, and the observation of some, who found the breadth of the ring to increase on the west side of the moon as emersion approached, together with the contrary sentiments of those whose judgment I shall always revere" (Newton is most probably referred to), "makes me less confident, especially in a matter whereto I confess I gave not all the attention requisite." He concludes by declining to decide whether the "enlightened atmosphere," which the appearance "in all respects resembled," "belonged to sun or moon."[169]

A French Academician, who happened to be in London at the time, was less guarded in expressing an opinion. The Chevalier de Louville declared emphatically for the lunar atmospheric theory of the corona,[170] and his authority carried great weight. It was, however, much discredited by an observation made by Maraldi in 1724, to the effect that the luminous ring, instead of travelling *with* the moon, was traversed *by* it.[171] This was in reality decisive, though, as usual, belief lagged far behind demonstration. In 1715 a novel explanation had been offered by Delisle and Lahire,[172] supported by experiments regarded at the time as perfectly satisfactory. The aureola round the eclipsed sun, they argued, is simply a result of the *diffraction*, or apparent bending of the sunbeams that graze the surface of the lunar globe—an effect of the same kind as the coloured fringes of shadows. And this view prevailed amongst men of science until (and even after) Brewster showed, with clear and simple decisiveness, that such an effect could by no possibility be appreciable at our distance from the moon.[173] Don José Joaquim de Ferrer, however, who observed a total eclipse of the sun at Kinderhook, in the State of New York, on June 16, 1806, ignoring this refined optical *rationale*, considered two alternative explanations of the phenomenon as alone possible. The bright ring round the moon must be due to the illumination either of a lunar or of a solar atmosphere. If the former, he calculated that it should have a height fifty times that of the earth's gaseous envelope. "Such an atmosphere," he rightly concluded, "cannot belong to the moon, but must without any doubt belong to the sun."[174] But he stood alone in this unhesitating assertion.

The importance of the problem was first brought fully home to astronomers by the eclipse of 1842. The brilliant and complex appearance which on that occasion challenged the attention of so many observers, demanded and received, no longer the casual attention hitherto bestowed upon it, but the most earnest study of those interested in the progress of science. Nevertheless, it was only by degrees, and through a process of "exclusions" (to use a Baconian phrase) that the corona was put in its right place as a solar appendage. As every other available explanation proved inadmissible and dropped out of sight, the broad presentation of fact remained, which, though of sufficiently obvious interpretation, was long and persistently misconstrued. Nor was it until 1869 that absolutely decisive evidence on the subject was forthcoming, as we shall see further on.

Sir John Herschel, writing to his venerable aunt, relates that when the brilliant red flames burst into view behind the dark moon on the morning of the 8th of July, 1842, the populace of Milan, with the usual inconsequence of a crowd, raised the shout, "*Es leben die Astronomen!*"[175] In reality, none were less prepared for their apparition than the class to whom the applause due to the magnificent spectacle was thus adjudged. And in some measure through their own fault, for many partial hints and some distinct statements from earlier observers had given unheeded notice that some such phenomenon might be expected to attend a solar eclipse.

What we now call the "chromosphere" is an envelope of glowing gases, by which the sun is completely covered, and from which the "prominences" are emanations, eruptive or flame-like. Now, continual indications of the presence of this fire-ocean had been detected during eclipses in the eighteenth and nineteenth centuries. Captain Stannyan, describing in a letter to Flamsteed an occurrence of the kind witnessed by him at Berne on May 1 (o.s.), 1706, says that the sun's "getting out of the eclipse was preceded by a blood-red streak of light from its left limb."[176] A precisely similar appearance was noted by both Halley and De Louville in 1715; during annular eclipses by Lord Aberdour in 1737,[177] and by Short in 1748,[178] the tint of the ruby border being, however, subdued to "brown" or "dusky red" by the surviving sunlight; while observations identical in character were made at Amsterdam in 1820,[179] at Edinburgh by Henderson in 1836, and at New York in 1838.[180]

"Flames" or "prominences," if more conspicuous, are less constant in their presence than the glowing stratum from which they spring. The first to describe them was a Swedish professor named Vassenius, who observed a total eclipse at Gothenburg, May 2 (o.s.), 1733.[181] His astonishment equalled his admiration when he perceived, just outside the edge of the lunar disc, and suspended, as it seemed, in the coronal atmosphere, three or four reddish spots or clouds, one of which was so large as to be detected with the naked eye. As to their nature, he did not even offer a speculation, further than by tacitly referring them to the moon. The observation was repeated in 1778 by a Spanish Admiral, but with no better success in directing efficacious attention to the phenomenon. Don Antonio Ulloa was on board his ship the *Espagne* in passage from the Azores to Cape St. Vincent on the 24th of June in that year, when a total eclipse of the sun occurred, of which he has left a valuable description. His notices of the corona are full of interest; but what just now concerns us is the appearance of "a red luminous point" "near the edge of the moon," which gradually increased in size as the moon moved away from it, and was visible during about a minute and a quarter.[182] He was satisfied that it belonged to the sun because of its fiery colour and growth in magnitude, and supposed that it was occasioned by some crevice or inequality in the moon's limb, through which the solar light penetrated.

Allusions less precise, both prior and subsequent, which it is now easy to refer to similar objects (such as the "slender columns of smoke" seen by Ferrer)[183] might be detailed; but the evidence already adduced suffices to show that the prominences viewed with such amazement in 1842 were no unprecedented or even unusual phenomenon.

It was more important, however, to decide what was their nature than whether their appearance might have been anticipated. They were generally, and not very incorrectly, set down as solar clouds. Arago believed them to shine by reflected light,[184] but the Abbé Peytal rightly considered them to be self-luminous. Writing in a Montpellier paper of July 16, 1842, he declared that we had now become assured of the existence of a third or outer solar envelope, composed of a glowing substance of a bright rose tint, forming mountains of prodigious elevation, analogous in character to the clouds piled above our horizons.[185] This first distinct recognition of a very important feature of our great luminary was probably founded on an observation made by Bérard at Toulon during the then recent eclipse, "of a very fine red band, irregularly dentelated, or, as it were, crevassed here and there,"[186] encircling a large arc of the moon's circumference. It can hardly, however, be said to have attracted general notice until July 28, 1851. On that day a total eclipse took place, which was observed with considerable success in various parts of Sweden and Norway by a number of English astronomers. Mr. Hind saw, on the south limb of the moon, "a long range of rose-coloured flames,"[187] described by Dawes as "a low ridge of red prominences, resembling in outline the tops of a very irregular range of hills."[188] Airy termed the portion of this "rugged lines of projections" visible to him the *sierra*, and was struck with its brilliant light and "nearly scarlet" colour.[189] Its true character of a continuous solar envelope was inferred from these data by Grant, Swan, and Littrow, and was by Father Secchi, after the great eclipse of 1860,[190] formally accepted as established.

Several prominences of remarkable forms, especially one variously compared to a Turkish scimitar, a sickle, and a boomerang, were seen in 1851. In connection with them two highly significant circumstances were pointed out. First, that of the approximate coincidence between their positions and those of sun-spots previously observed.[191] Next, that "the moon passed over them, leaving them behind, and revealing successive portions as she advanced."[192] This latter perfectly well-attested fact was justly considered by the Astronomer Royal and others as affording absolute certainty of the solar dependence of these singular objects. Nevertheless sceptics were still found. M. Faye, of the French Academy, inclined to a lunar origin for them;[193] Feilitsch of Greifswald published in 1852 a treatise for the express purpose of proving all the luminous phenomena attendant on solar eclipses—corona, prominences and "sierra"—to be purely optical appearances.[194] Happily, however, the unanswerable arguments of the photographic camera were soon to be made available against such hardy incredulity.

Thus, the virtual discovery of the solar appendages, both coronal and chromospheric, may be said to have been begun in 1842, and completed in 1851. The current Herschelian theory of the solar constitution remained, however, for the time, intact. Difficulties, indeed, were thickening around it; but their discussion was perhaps felt to be premature, and they were permitted to accumulate without debate, until fortified by fresh testimony into unexpected and overwhelming preponderance.

FOOTNOTES:

[131] Kosmos, Bd. iii., p. 409; Lalande, *Bibliographie Astronomique*, pp. 179, 202.

[132] R. Wolf, *Die Sonne und ihre Flecken*, p. 9. Marius himself, however, seems to have held the Aristotelian terrestrial-exhalation theory of cometary origin. See his curious little tract, *Astronomische und Astrologische Beschreibung der Cometen*, Nürnberg, 1619.

[133] *Phil. Trans.*, vol. xxvii., p. 274. *Umbræ* (now called *penumbræ*) are spaces of half-shadow which usually encircle spots. *Faculæ* (“little torches,” so named by Scheiner) are bright streaks or patches closely associated with spots.

[134] *Mém. Ac. Sc.*, 1776 (pub. 1779), p. 507. D. Cassini, however, first put forward about 1671 the hypothesis alluded to in the text. See Delambre, *Hist. de l’Astr. Mod.*, t. ii., p. 694; and *Kosmos*, Bd. iii., p. 410.

[135] *Phil. Trans.*, vol. lxiv., part i., pp. 7-11.

[136] *Rosa Ursina*, lib. iv., p. 507.

[137] R. Wolf, *Die Sonne und ihre Flecken*, p. 12.

[138] Schellen, *Die Spectralanalyse*, Bd. ii., p. 56 (3rd ed.).

[139] *Phil. Trans.*, vol. lxiv., p. 20.

[140] *Ibid.*, vol. lxxxv., 1795, p. 63.

[141] *Phil. Trans.*, vol. xci., 1801, p. 303.

[142] The supposed opaque or protective stratum beneath the photosphere was named by him “planetary,” from the analogy of terrestrial clouds.

[143] *Ibid.*, p. 305.

[144] *Novum Organum*, lib. ii. aph. 20.

[145] Brewster’s *Life of Newton*, vol. ii., p. 103.

[146] *Beschäftigungen d. Berl. Ges. Naturforschender Freunde*, Bd. ii., p. 233.

[147] *Gentleman’s Magazine*, 1787, vol. ii., p. 636.

[148] *Results*, etc., p. 432.

[149] *Ibid.*, p. 434.

[150] See *ante*, p. 31.

[151] *Memoir of Francis Baily, Mem. R. A. S.*, vol. xv., p. 524.

[152] *Mem. R. A. S.*, vol. x., pp. 5-6.

[153] *Ibid.*, pp. 14-17.

[154] *Mem. R. A. S.*, vol. xv., pp. 4-6.

[155] *Ibid.*, p. 16.

[156] *Annuaire*, 1846, p. 409.

[157] *Ibid.*, p. 317.

[158] *Ibid.*, p. 322.

[159] *Phil. Trans.*, vol. xl., p. 192.

[160] *Mem. R. A. S.*, vol. x., p. 17.

[161] *Ann. du Bureau des Long.*, 1846, p. 309.

[162] *De Facie in Orbe Lunæ*, xix., 10. Cf. Grant, *Astr. Nach.*, No. 1838. As to the phenomenon mentioned by Philostratus in his *Life of Apollonius* (viii. 23), see W. T. Lynn, *Observatory*, vol. ix., p. 128.

[163] Schmidt, *Astr. Nach.*, No. 1832.

[164] *Astronomiæ Pars Optica*, *Op. omnia*, t. ii., p. 317.

[165] *De Stellâ Novâ*, *Op.*, t. ii., pp. 696, 697.

[166] *Astr. Pars Op.*, p. 320.

[167] *Mém. de l'Ac. des Sciences*, 1706, p. 119.

[168] A digit = 1/12 of the solar diameter.

[169] *Phil. Trans.*, vol. xxix., pp. 247-249.

[170] *Mém. de l'Ac. des Sciences*, 1715; *Histoire*, p. 49; *Mémoires*, pp. 93-98.

[171] *Ibid.*, 1724, p. 178.

[172] *Mém. de l'Ac. des Sciences*, 1715, pp. 161, 166-169.

[173] *Ed. Ency.*, art. *Astronomy*, p. 635.

[174] *Trans. Am. Phil. Soc.*, vol. vi., p. 274.

[175] *Memoir of Caroline Herschel*, p. 327.

[176] *Phil. Trans.*, vol. xxv., p. 2240.

[177] *Ibid.*, vol. xl., p. 182.

[178] *Ibid.*, vol. xlv., p. 586.

[179] *Mem. R. A. S.*, vol. i., pp. 145, 148.

[180] *American Journal of Science*, vol. xlii., p. 396.

[181] *Phil. Trans.*, vol. xxxviii., p. 134. Father Secchi, however, adverted to a distinct mention of a prominence observed in 1239 A.D. A description of a total eclipse of that date includes the remark, "Et quoddam foramen erat ignitum in circulo solis ex parte inferiore" (Muratori, *Rer. It. Scriptores*, t. xiv., col. 1097). The "circulus solis" of course signifies the corona.

[182] *Phil. Trans.*, vol. lxix., p. 114.

[183] *Trans. Am. Phil. Soc.*, vol. vi., 1809, p. 267.

[184] *Annuaire*, 1846, p. 460.

[185] *Ibid.*, p. 439, *note*.

[186] *Ibid.*, p. 416.

[187] *Mem. R. A. S.*, vol. xxi., p. 82.

[188] *Ibid.*, p. 90.

[189] *Ibid.*, pp. 7, 8.

[190] *Le Soleil*, t. i., p. 386.

[191] By Williams and Stanistreet, *Mem. R. A. S.*, vol. xxi., pp. 54, 56. Santini had made a similar observation at Padua in 1842. Grant, *Hist. Astr.*, p. 401.

[192] Lassell in *Month. Not.*, vol. xii., p. 53.

[193] *Comptes Rendus*, t. xxxiv., p. 155.

[194] *Optische Untersuchungen*, and *Zeitschrift für populäre Mittheilungen*, Bd. i., 1860, p. 201.

CHAPTER IV

PLANETARY DISCOVERIES

In the course of his early gropings towards a law of the planetary distances, Kepler tried the experiment of setting a planet, invisible by reason of its smallness, to revolve in the vast region of seemingly desert space separating Mars from Jupiter.[195] The disproportionate magnitude of the same interval was explained by Kant as due to the overweening size of Jupiter. The zone in which each planet moved was, according to the philosopher of Königsberg, to be regarded as the empty storehouse from which its materials had been derived. A definite relation should thus exist between the planetary masses and the planetary intervals.[196] Lambert, on the other hand, sportively suggested that the body or bodies (for it is noticeable that he speaks of them in the plural) which once bridged this portentous gap in the solar system, might, in some remote age, have been swept away by a great comet, and forced to attend its wanderings through space.[197]

These speculations were destined before long to assume a more definite form. Johann Daniel Titius, a professor at Wittenberg (where he died in 1796), pointed out in 1772, in a note to a translation of Bonnet's *Contemplation de la Nature*,[198] the existence of a remarkable symmetry in the disposition of the bodies constituting the solar system. By a certain series of numbers, increasing in regular progression,[199] he showed that the distances of the six known planets from the sun might be represented with a close approach to accuracy. But with one striking interruption. The term of the series succeeding that which corresponded to the orbit of Mars was without a celestial representative. The orderly flow of the sequence was thus singularly broken. The space where a planet should —in fulfilment of the "Law"—have revolved, was, it appeared, untenanted. Johann Elert Bode, then just about to begin his long career as leader of astronomical thought and work at Berlin, marked at once the anomaly, and filled the vacant interval with a hypothetical planet. The discovery of Uranus, at a distance falling but slightly short of perfect conformity with the law of Titius, lent weight to a seemingly hazardous prediction, and Von Zach was actually at the pains, in 1785, to calculate what he termed "analogical" elements[200] for this unseen and (by any effect or influence) *unfelt* body. The search for it, through confessedly scarcely less chimerical than that of alchemists for the philosopher's stone, he kept steadily in view for fifteen years, and at length (September 21, 1800) succeeded in organising, in combination with five other German astronomers assembled at Lilienthal, a force of what he jocularly termed celestial police, for the express purpose of tracking and intercepting the fugitive subject of the sun. The zodiac was accordingly divided for purposes of scrutiny into twenty-four zones; their apportionment to separate observers was in part effected, and the association was rapidly getting into working order, when news arrived that the missing planet had been found, through no systematic plan of search, but by the diligent, though otherwise directed labours of a distant watcher of the skies.

Giuseppe Piazzi was born at Ponte in the Valtelline, July 16, 1746. He studied at various places and times under Tiraboschi, Beccaria, Jacquier, and Le Sueur; and having entered the Theatine order of monks at the age of eighteen, he taught philosophy, science, and theology in several of the Italian cities, as well as in Malta, until 1780, when the chair of mathematics in the University of Palermo was offered to and accepted by him. Prince Caramanico, then viceroy of Sicily, had scientific leanings, and was easily won over to the project of building an observatory, a commodious foundation for which was afforded by one of the towers of the viceregal palace. This architecturally incongruous addition to an ancient Saracenic edifice—once the abode of Kelbite and Zirite Emirs—was completed in February, 1791. Piazzi, meanwhile, had devoted nearly three years to the assiduous study of his new profession, acquiring a practical knowledge of Lalande's methods at the École Militaire, and of Maskelyne's at the Royal Observatory; and returned to Palermo in 1789, bringing with him, in the great five-foot circle which he had prevailed upon Ramsden to construct, the most perfect measuring instrument hitherto employed by an astronomer.

He had been above nine years at work on his star-catalogue, and was still profoundly unconscious that a place amongst the Lilienthal band[201] of astronomical detectives was being held in reserve for him, when, on the first evening of the nineteenth century, January 1, 1801, he noticed the position of an eighth-magnitude star in a part of the constellation Taurus to which an error of Wollaston's had directed his special attention. Reobserving, according to his custom, the same set of fifty stars on four consecutive nights, it seemed to him, on the 2nd, that the one in question had slightly shifted its position to the west; on the 3rd he assured himself of the fact, and believed that he had chanced upon a new kind of comet without tail or coma. The wandering body, whatever its nature, exchanged retrograde for direct motion on January 14,[202] and was carefully watched by Piazzi until February 11, when a dangerous illness interrupted his observations. He had, however, not omitted to give notice of his discovery; but so precarious were communications in those unpeaceful times, that his letter to Oriani of January 23 did not reach Milan until April 5, while a missive of one day later addressed to Bode came to hand at Berlin, March 20. The delay just afforded time for the publication, by a young philosopher of Jena named Hegel, of a "Dissertation" showing, by the clearest light of reason, that the number of the planets could not exceed seven, and exposing the folly of certain devotees of induction who sought a new celestial body merely to fill a gap in a numerical series.[203]

Unabashed by speculative scorn, Bode had scarcely read Piazzi's letter when he concluded that it referred to the precise body in question. The news spread rapidly, and created a profound sensation, not unmixed with alarm lest this latest addition to the solar family should have been found only to be again lost. For by that time Piazzi's moving star was too near the sun to be any longer visible, and in order to rediscover it after conjunction a tolerably accurate knowledge of its path was indispensable. But a planetary orbit had never before been calculated from such scanty data as Piazzi's observation afforded;[204] and the attempts made by nearly every astronomer of note in Germany to compass the problem were manifestly inadequate, failing even to account for the positions in which the body had been actually seen, and *à fortiori* serving only to mislead as to the places where, from September, 1801, it ought once more to have become discernible. It was in this extremity that the celebrated mathematician Gauss came to the rescue. He was then in his twenty-fifth year, and was earning his bread by tuition at Brunswick, with many possibilities, but no settled career before him. The news from Palermo may be said to have converted him from an arithmetician into an astronomer. He was already in possession of a new and more general method of computing elliptical orbits; and the system of "least squares," which he had devised though not published, enabled him to extract the most probable result from a given set of observations. Armed with these novel powers, he set to work; and the communication in November of his elements and ephemeris for the lost object revived the drooping hopes of the little band of eager searchers. Their patience, however, was to be still further tried. Clouds, mist, and sleet seemed to have conspired to cover the retreat of the fugitive; but on the last night of the year the sky cleared unexpectedly with the setting in of a hard frost, and there, in the north-western part of Virgo, nearly in the position assigned by Gauss to the runaway planet, a strange star was discerned by Von Zach[205] at Gotha, and on a subsequent evening—the anniversary of the original discovery—by Olbers at Bremen. The name of Ceres (as the tutelary goddess of Sicily) was, by Piazzi's request, bestowed upon this first known of the numerous, and probably all but innumerable family of the minor planets.

The recognition of the second followed as the immediate consequence of the detection of the first. Olbers had made himself so familiar with the positions of the small stars along the track of the long-missing body, that he was at once struck (March 28, 1802) with the presence of an intruder near the spot where he had recently identified Ceres. He at first believed the new-comer to be a variable star usually inconspicuous, but just then at its maximum of brightness; but within two hours he had convinced himself that it was no *fixed* star, but a rapidly moving object. The aid of Gauss was again invoked, and his prompt calculations showed that this fresh celestial acquaintance (named "Pallas" by Olbers), revolved round the sun at nearly the same mean distance as Ceres, and was beyond question of a strictly analogous character.

This result was perplexing in the extreme. The symmetry and simplicity of the planetary scheme appeared fatally compromised by the admission of many, where room could, according to old-fashioned rules, only be found for one. A daring hypothesis of Olbers's invention provided an exit from the difficulty. He supposed that both Ceres and Pallas were fragments of a primitive trans-Martian planet, blown to pieces in the remote past, either by the action of internal forces or by the impact of a comet; and predicted that many more such fragments would be found to circulate in the same region. He, moreover, pointed out that these numerous orbits, however much they might differ in other respects, must all have a common line of intersection,[206] and that the bodies moving in them must consequently pass, at each revolution, through two opposite points of the heavens, one situated in the Whale, the other in the constellation of the Virgin, where already Pallas had been found and Ceres recaptured. The intimation that fresh discoveries might be expected in those particular regions was singularly justified by the detection of two bodies now known respectively as Juno and Vesta. The first was found near the predicted spot in Cetus by Harding, Schröter's assistant at Lilienthal, September 2, 1804; the second by Olbers himself in Virgo, after three years of persistent scrutiny, March 29, 1807.

The theory of an exploded planet now seemed to have everything in its favour. It required that the mean or average distances of the newly-discovered bodies should be nearly the same, but admitted a wide range of variety in the shapes and positions of their orbits, provided always that they preserved common points of intersection. These conditions were fulfilled with a striking approach to exactness. Three of the four "asteroids" (a designation introduced by Sir. W. Herschel[207]) conformed with very approximate precision to "Bode's law" of distances; they all traversed, in their circuits round the sun, nearly the same parts of Cetus and Virgo; while the eccentricities and inclinations of their paths departed widely from the planetary type—that of Pallas, to take an extreme instance, making with the ecliptic an angle of nearly 35°. The minuteness of these bodies appeared further to strengthen the imputation of a fragmentary character. Herschel estimated the diameter of Ceres at 162, that of Pallas at 147 miles.[208] But these values are now known to be considerably too small. A suspected variability of brightness in some of the asteroids, somewhat hazardously explained as due to the irregularities of figure to be expected in cosmical *potsherds* (so to speak), was added to the confirmatory evidence.[209] The strong point of the theory, however, lay not in what it explained, but in what it had predicted. It had been twice confirmed by actual exploration of the skies, and had produced, in the recognition of Vesta, the first recorded instance of the *premeditated* discovery of a heavenly body.

The view not only commended itself to the facile imagination of the unlearned, but received the sanction of the highest scientific authority. The great Lagrange bestowed upon it his analytical *imprimatur*, showing that the explosive forces required to produce the supposed catastrophe came well within the bounds of possibility; since a velocity of less than twenty times that of a cannon-ball leaving the gun's mouth would have sufficed, according to his calculation, to launch the asteroidal fragments on their respective paths. Indeed, he was disposed to regard the hypothesis of disruption as more generally available than its author had designed it to be, and proposed to supplement with it, as explanatory of the eccentric orbits of comets, the nebular theory of Laplace, thereby obtaining, as he said, "a complete view of the origin of the planetary system more conformable to Nature and mechanical laws than any yet proposed."[210]

Nevertheless the hypothesis of Olbers has not held its ground. It seemed as if all the evidence available for its support had been produced at once and spontaneously, while the unfavourable items were elicited slowly, and, as it were, by cross-examination. A more extended acquaintance with the group of bodies whose peculiarities it was framed to explain has shown them, after all, as recalcitrant to any such explanation. Coincidences at the first view significant and striking have been swamped by contrary examples; and a hasty general conclusion has, by a not uncommon destiny, at last perished under the accumulation of particulars. Moreover, as has been remarked by Professor Newcomb,[211] mutual perturbations would rapidly efface all traces of a common disruptive origin, and the catastrophe, to be perceptible in its effects, should have been comparatively recent.

A new generation of astronomers had arisen before any additions were made to the little family of the minor planets. Piazzi died in 1826, Harding in 1834, Olbers in 1840; all those who had prepared or participated in the first discoveries passed away without witnessing their resumption. In 1830, however, a certain Hencke, ex-postmaster in the Prussian town of Driessen, set himself to watch for new planets, and after fifteen long years his patience was rewarded. The asteroid found by him, December 8, 1845, received the name of Astræa, and his further prosecution of the search resulted, July 1, 1847, in the discovery of Hebe. A few weeks later (August 13), John Russell Hind (1823-1893), after many months' exploration from Mr. Bishop's observatory in the Regent's Park, picked up Iris, and October 18, Flora.[212] The next on the list was Metis, found by Mr. Graham, April 25, 1848, at Markree, in Ireland.[213] At the close of the period to which our attention is at present limited, the number of these small bodies known to astronomy was thirteen; and the course of discovery has since proceeded far more rapidly and with less interruption.

Both in itself and in its consequences the recognition of the minor planets was of the highest importance to science. The traditional ideas regarding the constitution of the solar system were enlarged by the admission of a new class of bodies, strongly contrasted, yet strictly co-ordinate with the old-established planetary order; the profusion of resource, so conspicuous in the living kingdoms of Nature, was seen to prevail no less in the celestial spaces; and some faint preliminary notion was afforded of the indefinite complexity of relations underlying the apparent simplicity of the majestic scheme to which our world belongs. Both theoretical and practical astronomy derived profit from the admission of these apparently insignificant strangers to the rights of citizenship of the solar system. The disturbance of their motions by their giant neighbours afforded a more accurate knowledge of the Jovian mass, which Laplace had taken about 1/50 too small; the anomalous character of their orbits presented geometers with highly stimulating problems in the theory of perturbation; while the exigencies of the first discovery had produced the *Theoria Motus*, and won Gauss over to the ranks of calculating astronomy. Moreover, the sure prospect of further detections powerfully incited to the exploration of the skies; observers became more numerous and more zealous in view of the prizes held out to them;

star-maps were diligently constructed, and the sidereal multitude strewn along the great zodiacal belt acquired a fresh interest when it was perceived that its least conspicuous member might be a planetary shred or projectile in the dignified disguise of a distant sun. Harding's "Celestial Atlas," designed for the special purpose of facilitating asteroidal research, was the first systematic attempt to represent to the eye the *telescopic* aspect of the heavens. It was while engaged on its construction that the Lilienthal observer successfully intercepted Juno on her passage through the Whale in 1804; whereupon promoted to Göttingen, he there completed, in 1822, the arduous task so opportunely entered upon a score of years previously. Still more important were the great star-maps of the Berlin Academy, undertaken at Bessel's suggestion, with the same object of distinguishing errant from fixed stars, and executed, under Encke's supervision, during the years 1830-59. They have played a noteworthy part in the history of planetary discovery, nor of the minor kind alone.

We have now to recount an event unique in scientific history. The discovery of Neptune has been characterised as the result of a "movement of the age,"[214] and with some justice. It had become necessary to the integrity of planetary theory. Until it was accomplished, the phantom of an unexplained anomaly in the orderly movements of the solar system must have continued to haunt astronomical consciousness. Moreover, it was prepared by many, suggested as possible by not a few, and actually achieved, simultaneously, independently, and completely, by two investigators.

The position of the planet Uranus was recorded as that of a fixed star no less than twenty times between 1690 and the epoch of its final detection by Herschel. But these early observations, far from affording the expected facilities for the calculation of its orbit, proved a source of grievous perplexity. The utmost ingenuity of geometers failed to combine them satisfactorily with the later Uranian places, and it became evident, either that they were widely erroneous, or that the revolving body was wandering from its ancient track. The simplest course was to reject them altogether, and this was done in the new Tables published in 1821 by Alexis Bouvard, the indefatigable computating partner of Laplace. But the trouble was not thus to be got rid of. After a few years fresh irregularities began to appear, and continued to increase until absolutely "intolerable." It may be stated as illustrative of the perfection to which astronomy had been brought, that divergencies regarded as menacing the very foundation of its theories never entered the range of unaided vision. In other words, if the theoretical and the real Uranus had been placed side by side in the sky, they would have seemed, to the sharpest eye, to form a single body.[215]

The idea that these enigmatical disturbances were due to the attraction of an unknown exterior body was a tolerably obvious one; and we accordingly find it suggested in many different quarters. Bouvard himself was perhaps the first to conceive it. He kept the possibility continually in view, and bequeathed to his nephew's diligence the inquiry into its reality when he felt that his own span was drawing to a close; but before any progress had been made with it, he had already (June 7, 1843) “ceased to breathe and to calculate.” The Rev. T. J. Hussey actually entertained in 1834 the notion, but found his powers inadequate to the task, of assigning an approximate place to the disturbing body; and Bessel, in 1840, laid his plans for an assault in form upon the Uranian difficulty, the triumphant exit from which fatal illness frustrated his hopes of effecting or even witnessing.

The problem was practically untouched when, in 1841, an undergraduate of St. John’s College, Cambridge, formed the resolution of grappling with it. The projected task was an arduous one. There were no guiding precedents for its conduct. Analytical obstacles had to be encountered so formidable as to appear invincible even to such a mathematician as Airy. John Couch Adams, however, had no sooner taken his degree, which he did as senior wrangler in January, 1843, than he set resolutely to work, and on October 21, 1845, was able to communicate to the Astronomer Royal numerical estimates of the elements and mass of the unknown planet, together with an indication of its actual place in the heavens. These results, it has been well said,[216] gave “the final and inexorable proof” of the validity of Newton’s Law. The date October 21, 1845, “may therefore be regarded as marking a distinct epoch in the history of gravitational astronomy.”

Sir George Biddell Airy had begun in 1835 his long and energetic administration of the Royal Observatory, and was already in possession of data vitally important to the momentous inquiry then on foot. At his suggestion, and under his superintendence, the reduction of all the planetary observations made at Greenwich from 1750 onwards had been undertaken in 1833. The results, published in 1846, constituted a permanent and universal stock of materials for the correction of planetary theory. But in the meantime, investigators, both native and foreign, were freely supplied with the “places and errors,” which, clearly exhibiting the discrepancies between observation and calculation—between what *was* and what was *expected*—formed the very groundwork of future improvements.

Mr. Adams had no reason to complain of official discourtesy. His labours received due and indispensable aid; but their purpose was regarded as chimerical. “I have always,” Sir George Airy wrote,[217] “considered the correctness of a distant mathematical result to be a subject rather of moral than of mathematical evidence.” And that actually before him seemed, from its very novelty, to incur a suspicion of unlikelihood. No problem in planetary disturbance had heretofore been attacked, so to speak, from the rear. The inverse method was untried, and might well be deemed impracticable. For the difficulty of determining the perturbations produced by a given planet is small compared with the difficulty of finding a planet by its resulting perturbations. Laplace might have quailed before it; yet it was now grappled with as a first essay in celestial dynamics. Moreover, Adams unaccountably neglected to answer until too late a question regarded by Airy in the light of an *experimentum crucis* as to the soundness of the new theory. Nor did he himself take any steps to obtain a publicity which he was more anxious to merit than to secure.

The investigation consequently remained buried in obscurity. It is now known that had a search been instituted in the autumn of 1845 for the remote body whose existence had been so marvellously foretold, it would have been found within *three and a half lunar diameters* (1° 49′) of the spot assigned to it by Adams.

A competitor, however, equally daring and more fortunate—*audax fortunâ adjutus,* as Gauss said of him—was even then entering the field. Urbain Jean Joseph Leverrier, the son of a small Government *employé* in Normandy, was born at Saint-Lô, March 11, 1811. He studied with brilliant success at the École Polytechnique, accepted the post of astronomical teacher there in 1837, and, "docile to circumstance," immediately concentrated the whole of his vast, though as yet undeveloped powers upon the formidable problems, of celestial mechanics. He lost no time in proving to the mathematical world that the race of giants was not extinct. Two papers on the stability of the solar system, presented to the Academy of Sciences, September 16 and October 14, 1839, showed him to be the worthy successor of Lagrange and Laplace, and encouraged hopes destined to be abundantly realised. His attention was directed by Arago to the Uranian difficulty in 1845, when he cheerfully put aside certain intricate cometary researches upon which he happened to be engaged, in order to obey with dutiful promptitude the summons of the astronomical chief of France. In his first memoir on the subject (communicated to the Academy, November 10, 1845), he proved the inadequacy of all known causes of disturbance to account for the vagaries of Uranus; in a second (June 1, 1848), he demonstrated that only an exterior body, occupying at a certain date a determinate position in the zodiac, could produce the observed effects; in a third (August 31, 1846), he assigned the orbit of the disturbing body, and announced its visibility as an object with a sensible disc about as bright as a star of the eighth magnitude.

The question was now visibly approaching an issue. On September 10, Sir John Herschel declared to the British Association respecting the hypothetical new planet: "We see it as Columbus saw America from the coast of Spain. Its movements have been felt, trembling along the far-reaching line of our analysis with a certainty hardly inferior to that of ocular demonstration." Less than a fortnight later, September 23, Professor Galle, of the Berlin Observatory, received a letter from Leverrier requesting his aid in the telescopic part of the inquiry already analytically completed. He directed his refractor to the heavens that same night, and perceived, within less than a degree of the spot indicated, an object with a measurable disc nearly three seconds in diameter. Its absence from Bremiker's recently-completed map of that region of the sky showed it to be no star, and its movement in the predicted direction confirmed without delay the strong persuasion of its planetary nature. [218]

In this remarkable manner the existence of the remote member of our system known as "Neptune" was ascertained. But the discovery, which faithfully reflected the duplicate character of the investigation which led to it, had been already secured at Cambridge before it was announced from Berlin. Sir George Airy's incredulity vanished in the face of the striking coincidence between the position assigned by Leverrier to the unknown planet in June, and that laid down by Adams in the previous October; and on the 9th of July he wrote to Professor Challis, director of the Cambridge Observatory, recommending a search with the great Northumberland equatoreal. Had a good star-map been at hand, the process would have been a simple one; but of Bremiker's "Hora XXI." no news had yet reached England, and there was no other sufficiently comprehensive to be available for an inquiry which, in the absence of such aid, promised to be both long and laborious. As the event proved, it might have been neither. "After four days of observing," Challis wrote, October 12, 1846, to Airy, "the planet was in my grasp if only I had examined or mapped the observations."[219] Had he done so, the first honours in the discovery, both theoretical and optical, would have fallen to the University of Cambridge. But Professor Challis had other astronomical avocations to attend to, and, moreover, his faith in the precision of the indications furnished to him was, by his own confession, a very feeble one. For both reasons he postponed to a later stage of the proceedings the discussion and comparison of the data nightly furnished to him by his telescope, and thus allowed to lie, as it were, latent in his observations the momentous result which his diligence had insured, but which his delay suffered to be anticipated.[220]

Nevertheless, it should not be forgotten that the Berlin astronomer had two circumstances in his favour apart from which his swift success could hardly have been achieved. The first was the possession of a good star-map; the second was the clear and confident nature of Leverrier's instructions. "Look where I tell you," he seemed authoritatively to say, "and you will see an object such as I describe."[221] And in fact, not only Galle on the 23rd of September, but also Challis on the 29th, immediately after reading the French geometer's lucid and impressive treatise, picked out from among the stellar points strewing the zodiac, a small planetary disc, which eventually proved to be that of the precise body he had been in search of during two months.

The controversy that ensued had its ignominious side; but it was entered into by neither of the parties principally concerned. Adams bore the disappointment, which the dilatory proceedings at Greenwich and Cambridge had inflicted upon him, with quiet heroism. His silence on the subject of what another man would have called his wrongs remained unbroken to the end of his life;[222] and he took every opportunity of testifying his admiration for the genius of Leverrier.

Personal questions, however, vanish in the magnitude of the event they relate to. By it the last lingering doubts as to the absolute exactness of the Newtonian Law were dissipated. Recondite analytical methods received a confirmation brilliant and intelligible even to the minds of the vulgar, and emerged from the patient solitude of the study to enjoy an hour of clamorous triumph. For ever invisible to the unaided eye of man, a sister-globe to our earth was shown to circulate, in perpetual frozen exile, at thirty times its distance from the sun. Nay, the possibility was made apparent that the limits of our system were not even thus reached, but that yet profounder abysses of space might shelter obedient, though little favoured, members of the solar family, by future astronomers to be recognised through the sympathetic thrillings of Neptune, even as Neptune himself was recognised through the tell-tale deviations of Uranus.

It is curious to find that the fruit of Adams's and Leverrier's laborious investigations had been accidentally all but snatched half a century before it was ripe to be gathered. On the 8th, and again on the 10th of May, 1795, Lalande noted the position of Neptune as that of a fixed star, but perceiving that the two observations did not agree, he suppressed the first as erroneous, and pursued the inquiry no further. An immortality which he would have been the last to despise hung in the balance; the feather-weight of his carelessness, however, kicked the beam, and the discovery was reserved to be more hardly won by later comers.

Bode's Law did good service in the quest for a trans-Uranian planet by affording ground for a probable assumption as to its distance. A starting-point for approximation was provided by it; but it was soon found to be considerably at fault. Even Uranus is about 36 millions of miles nearer to the sun than the order of progression requires; and Neptune's vast distance of 2,800 million should be increased by no less than 800 million miles, and its period of 165 lengthened out to 225 years,[223] in order to bring it into conformity with the curious and unexplained rule which planetary discoveries have alternately tended to confirm and to invalidate.

Within seventeen days of its identification with the Berlin achromatic, Neptune was found to be attended by a satellite. This discovery was the first notable performance of the celebrated two-foot reflector[224] erected by Mr. Lassell at his suggestively named residence of Starfield, near Liverpool. William Lassell was a brewer by profession, but by inclination an astronomer. Born at Bolton in Lancashire, June 18, 1799, he closed a life of eminent usefulness to science, October 5, 1818, thus spanning with his well-spent years four-fifths of the momentous period which we have undertaken to traverse. At the age of twenty-one, being without the means to purchase, he undertook to construct telescopes, and naturally turned his attention to the reflecting sort, as favouring amateur efforts by the comparative simplicity of its structure. His native ingenuity was remarkable, and was developed by the hourly exigencies of his successive enterprises. Their uniform success encouraged him to enlarge his aims, and in 1844 he visited Birr Castle for the purpose of inspecting the machine used in polishing the giant speculum of Parsonstown. In the construction of his new instrument, however, he eventually discarded the model there obtained, and worked on a method of his own, assisted by the supreme mechanical skill of James Nasmyth. The result was a Newtonian of exquisite definition, with an aperture of two, and a focal length of twenty feet, provided by a novel artifice with the equatoreal mounting, previously regarded as available only for refractors.

This beautiful instrument afforded to its maker, October 10, 1846, a cursory view of a Neptunian attendant. But the planet was then approaching the sun, and it was not until the following July that the observation could be verified, which it was completely, first by Lassell himself, and somewhat later by Otto Stuve and Bond of Cambridge (U.S.). When it is considered that this remote object shines by reflecting sunlight reduced by distance to 1/900th of the intensity with which it illuminates our moon, the fact of its visibility, even in the most perfect telescopes, is a somewhat surprising one. It can only, indeed, be accounted for by attributing to it dimensions very considerable for a body of the secondary order. It shares with the moons of Uranus the peculiarity of retrograde motion; that is to say, its revolutions, running counter to the grand current of movement in the solar system, are performed from east to west, in a plane inclined at an angle of 35° to that of the ecliptic. Their swiftness serves to measure the mass of the globe round which they are performed. For while our moon takes twenty-seven days and nearly eight hours to complete its circuit of the earth, the satellite of Neptune, at a distance not greatly inferior, sweeps round its primary in five days and twenty-one hours, showing (according to a very simple principle of computation) that it is urged by a force seventeen times greater than the terrestrial pull upon the lunar orb. Combining this result with those of Professor Barnard's[225] and Dr. See's[226] recent measurements of the small telescopic disc of this farthest known planet, it is found that while in *mass* Neptune equals seventeen, in *bulk* it is equivalent to forty-nine earths. This is as much as to say that it is composed of relatively very light materials, or more probably of materials distended by internal heat, as yet unwasted by radiation into space, to about five times the volume they would occupy in the interior of our globe. The fact, at any rate, is fairly well ascertained, that the average density of Neptune is about twice that of water.

We must now turn from this late-recognised member of our system to bestow some brief attention upon the still fruitful field of discovery offered by one of the immemorial five. The family of Saturn, unlike that of its brilliant neighbour, has been gradually introduced to the notice of astronomers. Titan, the sixth Saturnian moon in order of distance, led the way, being detected by Huygens, March 25, 1655; Cassini made the acquaintance of four more between 1671 and 1684; while Mimas and Enceladus, the two innermost, were caught by Herschel in 1789, as they threaded their lucid way along the edge of the almost vanished ring. In the distances of these seven revolving bodies from their primary, an order of progression analogous to that pointed out by Titius in the planetary intervals was found to prevail; but with one conspicuous interruption, similar to that which had first suggested the search for new members of the solar system. Between Titan and Japetus—the sixth and seventh reckoning outwards—there was obviously room for another satellite. It was discovered on both sides of the Atlantic simultaneously, on the 19th of September, 1848. Mr. W. C. Bond, employing the splendid 15-inch refractor of the Harvard Observatory, noticed, September 16, a minute star situated in the plane of Saturn's rings. The same object was discerned by Mr. Lassell on the 18th. On the following evening, both observers perceived that the problematical speck of light kept up with, instead of being left behind by the planet as it moved, and hence inferred its true character.[227] Hyperion, the seventh by distance and eighth by recognition of Saturn's attendant train, is of so insignificant a size when compared with some of its fellow-moons (Titan is but little inferior to the planet Mars), as to have suggested to Sir John Herschel[228] the idea that it might be only one of several bodies revolving very close together—in fact, an *asteroidal satellite*; but the conjecture has, so far, not been verified.

The coincidence of its duplicate discovery was singularly paralleled two years later. Galileo's amazement when his "optic glass" revealed to him the "triple" form of Saturn—*planeta tergeminus*—has proved to be, like the laughter of the gods, "inextinguishable." It must revive in every one who contemplates anew the unique arrangements of that world apart known to us as the Saturnian system. The resolution of the so-called *ansæ*, or "handles," into one encircling ring by Huygens in 1655, the discovery by Cassini in 1675 of the division of that ring into two concentric ones, together with Laplace's investigation of the conditions of stability of such a formation, constituted, with some minor observations, the sum of the knowledge obtained, up to the middle of the last century, on the subject of this remarkable formation. The first place in the discovery now about to be related belongs to an American astronomer.

William Cranch Bond, born in 1789 at Portland, in the State of Maine, was a watchmaker, whom the solar eclipse of 1806 attracted to study the wonders of the heavens. When, in 1815, the erection of an observatory in connection with Harvard College, Cambridge, was first contemplated, he undertook a mission to England for the purpose of studying the working of similar institutions there, and on his return erected a private observatory at Dorchester, where he worked diligently for many years. Then at last, in 1843, the long-postponed design of the Harvard authorities was resumed, and on the completion of the new establishment, Bond, who had been from 1838 officially connected with the College and had carried on his scientific labours within its precincts, was offered and accepted the post of its director. Placed in 1847 in possession of one of the finest instruments in the world—a masterpiece of Merz and Mahler—he headed the now long list of distinguished Transatlantic observers. Like the elder Struve, he left an heir to his office and to his eminence, but George Bond unfortunately died in 1865, at the early age of thirty-nine, having survived his father but six years.

On the night of November 15, 1850—the air, remarkably enough, being so hazy that only the brightest stars could be perceived with the naked eye—William Bond discerned a dusky ring, extending about halfway between the inner brighter one and the globe of Saturn. A fortnight later, but before the observation had been announced in England, the same appearance was seen by the Rev. W. R. Dawes with the comparatively small refractor of his observatory at Wateringbury, and on December 3 was described by Mr. Lassell (then on a visit to him) as "something like a crape veil covering a part of the sky within the inner ring."[229] Next morning the *Times* containing the report of Bond's discovery reached Wateringbury. The most surprising circumstance in the matter was that the novel appendage had remained so long unrecognised. As the rings opened out to their full extent, it became obvious with very moderate optical assistance; yet some of the most acute observers who have ever lived, using instruments of vast power, had heretofore failed to detect its presence. It soon appeared, however, that Galle of Berlin[230] had noticed, June 10, 1838, a veil-like extension of the lucid ring across half the dark space separating it from the planet; but the observation, although communicated at the time to the Berlin Academy of Sciences, had remained barren. Traces of the dark ring, moreover, were found in drawings executed by Campani in 1664[231] and by Hooke in 1666;[232] while Picard (June 15, 1673),[233] Hadley (spring of 1720),[234] and Herschel,[235] had all undoubtedly seen it under the aspect of a dark bar or belt crossing the Saturnian globe. It was, then, of no recent origin; but there seemed reason to think that it had lately gained considerably in brightness. The full meaning of this suspected change it was reserved for later investigations to develop.

What we may, in a certain sense, call the closing result of the race for discovery, in which several observers seemed at that time to be engaged, was the establishment, on a satisfactory footing, of our acquaintance with the dependent system of Uranus. Sir William Herschel, whose researches formed, in so many distinct lines of astronomical inquiry, the starting-points of future knowledge, detected, January 11, 1787,[236] two Uranian moons, since called Oberon and Titania, and ascertained the curious circumstance of their motion in a plane almost at right angles to the ecliptic, in a direction contrary to that of all previously known denizens (other than cometary) of the solar kingdom. He believed that he caught occasional glimpses of four more, but never succeeded in assuring himself of their substantial existence. Even the two first remained unseen save by himself until 1828, when his son re-observed them with a 20-foot reflector, similar to that with which they had been originally discovered. Thenceforward they were kept fairly within view, but their four questionable companions, in spite of some false alarms of detection, remained in the dubious condition in which Herschel had left them. At last, on October 24, 1851,[237] after some years of fruitless watching, Lassell espied "Ariel" and "Umbriel," two Uranian attendants, interior to Oberon and Titania, and of about half their brightness; so that their disclosure is still reckoned amongst the very highest proofs of instrumental power and perfection. In all probability they were then for the first time seen; for although Professor Holden[238] made out a plausible case in favour of the fitful visibility to Herschel of each of them in turn, Lassell's argument[239] that the glare of the planet in Herschel's great specula must have rendered almost impossible the perception of objects so minute and so close to its disc, appears tolerably decisive to the contrary. Uranus is thus attended by four moons, and, so far as present knowledge extends, by no more. Among the most important of the "negative results"[240] secured by Lassell's observations at Malta during the years 1852-53 and 1861-65, were the convincing evidence afforded by them that, without great increase of optical power, no further Neptunian or Uranian satellites can be perceived, and the consequent relegation of Herschel's baffling quartette, notwithstanding the unquestioned place long assigned to them in astronomical text-books, to the Nirvana of non-existence.

FOOTNOTES:

[195] *Op.*, t. i., p. 107. He interposed, but tentatively only, another similar body between Mercury and Venus.

[196] *Allgemeine Naturgeschichte* (ed. 1798), pp. 118, 119.

[197] *Cosmologische Briefe*, No. 1 (quoted by Von Zach, *Monat. Corr.*, vol. iii., p. 592).

[198] Second ed., p. 7. See Bode, *Von dem neuen Hauptplaneten*, p. 43, *note*.

[199] The representative numbers are obtained by adding 1 to the following series (irregular, it will be observed, in its first member, which should be 1/2 instead of 0); 0, 3, 6, 12, 24, 48, etc. The formula is a purely empirical one, and is, moreover, completely at fault as regards the distance of Neptune.

[200] *Monat. Corr.*, vol. iii., p. 596.

[201] Wolf, *Geschichte der Astronomie*, p. 648.

[202] Such reversals of direction in the apparent movements of the planets are a consequence of the earth's revolution in its orbit.

[203] *Dissertatio Philosophica de Orbitis Planetarum*, 1801. See Wolf, *Gesch. d. Astr.*, p. 685.

[204] Observations on Uranus, as a supposed fixed star, went back to 1690.

[205] He had caught a glimpse of it on December 7, but was prevented by bad weather from verifying his suspicion. *Monat. Corr.*, vol. v., p. 171.

[206] Planetary fragments, hurled *in any direction*, and *with any velocity* short of that which would for ever release them from the solar sway, would continue to describe elliptic orbits round the sun, all passing through the scene of the explosion, and thus possessing a common line of intersection.

[207] *Phil. Trans.*, vol. xcii., part ii., p. 228.

[208] *Ibid.*, p. 218. In a letter to Von Zach of June 24, 1802, he speaks of Pallas as "almost incredibly small," and makes it only seventy English miles in diameter. *Monat. Corr.*, vol. vi., pp. 89, 90.

[209] Olbers, *Monat. Corr.*, vol. vi., p. 88.

[210] *Conn. d. Tems* for 1814, p. 218.

[211] *Popular Astronomy*, p. 327.

[212] *Month. Not.*, vol. vii., p. 299; vol. viii., p. 1.

[213] *Ibid.*, p. 146.

[214] Airy, *Mem. R. A. S.*, vol. xvi., p. 386.

[215] See Newcomb's *Pop. Astr.*, p. 359. The error of Uranus amounted, in 1844, to 2′; but even the tailor of Breslau, whose extraordinary powers of vision Humboldt commemorates (*Kosmos*, Bd. ii., p. 112), could only see Jupiter's first satellite at its greatest elongation, 2′ 15′. He might, however, possibly have distinguished two objects of *equal* lustre at a lesser interval.

[216] J. W. L. Glaisher, *Observatory*, vol. xv., p. 177.

[217] *Mem. R. A. S.*, vol. xvi., p. 399.

[218] For an account of D'Arrest's share in the detection see *Copernicus*, vol. ii., pp. 63, 96.

[219] *Mem. R. A. S.*, vol. xvi., p. 412.

[220] He had recorded the places of 3,150 stars (three of which were different positions of the planet), and was preparing to map them, when, October 1, news of the discovery arrived from Berlin. Prof. Challis's *Report*, quoted in Obituary Notice, *Month. Not.*, Feb., 1883, p. 170.

[221] See Airy in *Mem. R. A. S.*, vol. xvi., p. 411.

[222] He died January 21, 1892, in his 71st year.

[223] Ledger, *The Sun, its Planets and their Satellites*, p. 414.

[224] Presented by the Misses Lassell, after their father's death, to the Greenwich Observatory.

[225] *Astr. Jour.*, No. 508.

[226] *Report of U.S. Naval Observatory for 1900*, p. 15.

[227] Grant, *Hist. of Astr.*, p. 271.

[228] *Month. Not.*, vol. ix., p. 91.

[229] *Month. Not.*, vol. xi., p. 21.

[230] *Astr. Nach.*, No. 756 (May 2, 1851).

[231] *Phil. Trans.*, vol. i., p. 246. See H. T. Vivian, *Engl. Mech.*, April 20, 1894.

[232] Secchi, *Month. Not.*, vol. xiii., p. 248.

[233] Hind, *ibid.*, vol. xv., p. 32.

[234] Lynn, *Observatory*, Oct. 1, 1883; Hadley, *Phil. Trans.*, vol. xxxii., p. 385.

[235] Proctor, *Saturn and its System*, p. 64.

[236] *Phil. Trans.*, vol. lxxvii., p. 125.

[237] *Month. Not.*, vol. xi., p. 248.

[238] *Ibid.*, vol. xxxv., pp. 16-22.

[239] *Ibid.*, p. 26.

[240] *Ibid.*, vol. xli., p. 190.

CHAPTER V

COMETS

Newton showed that the bodies known as "comets," or *hirsute* stars, obey the law of gravitation; but it was by no means certain that the individual of the species observed by him in 1680 formed a permanent member of the solar system. The velocity, in fact, of its rush round the sun was quite possibly sufficient to carry it off for ever into the depths of space, there to wander, a celestial casual, from star to star. With another comet, however, which appeared two years later, the case was different. Edmund Halley, who afterwards succeeded Flamsteed as Astronomer Royal, calculated the elements of its orbit on Newton's principles, and found them to resemble so closely those similarly arrived at for comets observed by Peter Apian in 1531, and by Kepler in 1607, as almost to compel the inference that all three were apparitions of a single body. This implied its revolution in a period of about seventy-six years, and Halley accordingly fixed its return for 1758-9. So fully alive was he to the importance of the announcement that he appealed to a "candid posterity," in the event of its verification, to acknowledge that the discovery was due to an Englishman. The prediction was one of the test-questions put by Science to Nature, on the replies to which largely depend both the development of knowledge and the conviction of its reality. In the present instance, the answer afforded may be said to have laid the foundation of this branch of astronomy. Halley's comet punctually reappeared on Christmas Day, 1758, and effected its perihelion passage on the 12th of March following, thus proving beyond dispute that some at least of these erratic bodies are domesticated within our system, and strictly conform, if not to its unwritten customs (so to speak), at any rate to its fundamental laws. Their movements, in short, were demonstrated by the most unanswerable of all arguments—that of verified calculation—to be *calculable*, and their investigation was erected into a legitimate department of astronomical science.

This notable advance was the chief *result* obtained in the field of inquiry just now under consideration during the eighteenth century. But before it closed, its cultivation had received a powerful stimulus through the invention of an improved *method*. The name of Olbers has already been brought prominently before our readers in connection with asteroidal discoveries; these, however, were but chance excursions from the path of cometary research which he steadily pursued through life. An early predilection for the heavens was fixed in this particular direction by one of the happy inspirations of genius. As he was watching, one night in the year 1779, by the sick-bed of a fellow-student in medicine at Göttingen, an important simplification in the mode of computing the paths of comets occurred to him. Although not made public until 1797, "Olbers's method" was then universally adopted, and is still regarded as the most expeditious and convenient in cases where absolute rigour is not required. By its introduction, not only many a toilsome and thankless hour was spared, but workers were multiplied, and encouraged in the prosecution of labours more useful than attractive.

The career of Heinrich Olbers is a brilliant example of what may be done by an amateur in astronomy. He at no time did regular work in an observatory; he was never the possessor of a transit or any other fixed instrument; moreover, all the best years of his life were absorbed in the assiduous exercise of a toilsome profession. Born in 1758 at the village of Arbergen, where his father was pastor, he settled in 1781 as a physician in the neighbouring town of Bremen, and continued in active practice there for over forty years. It was thus only the hours which his robust constitution enabled him to spare from sleep that were available for his intellectual pleasures. Yet his recreation was, as Von Zach remarked,[241] no less prolific of useful results than the severest work of other men. The upper part of his house in the Sandgasse was fitted up with such instruments and appliances as restrictions of space permitted, and there, night after night during half a century and upwards, he discovered, calculated, or observed the cometary visitants of northern skies. Almost as effective in promoting the interests of science as the valuable work actually done by him, was the influence of his genial personality. He engaged confidence by his ready and discerning sympathy; he inspired affection by his benevolent disinterestedness; he quickened thought and awakened zeal by the suggestions of a lively and inventive spirit, animated with the warmest enthusiasm for the advancement of knowledge. Nearly every astronomer in Germany enjoyed the benefits of a frequently active correspondence with him, and his communications to the scientific periodicals of the time were numerous and striking. The motive power of his mind was thus widely felt and continually in action. Nor did it wholly cease to be exerted even when the advance of age and the progress of infirmity rendered him incapable of active occupation. He was, in fact, *alive* even to the last day of his long life of eighty-one years; and his death, which occurred March 2, 1840, left vacant a position which a rare combination of moral and intellectual qualities had conspired to render unique.

Amongst the many younger men who were attracted and stimulated by intercourse with him was Johann Franz Encke. But while Olbers became a mathematician because he was an astronomer, Encke became an astronomer because he was a mathematician. A born geometer, he was naturally sent to Göttingen and placed under the tuition of Gauss. But geometers are men; and the contagion of patriotic fervour which swept over Germany after the battle of Leipsic did not spare Gauss's promising pupil. He took up arms in the Hanseatic Legion, and marched and fought until the oppressor of his country was safely ensconced behind the ocean-walls of St. Helena. In the course of his campaigning he met Lindenau, the militant director of the Seeberg Observatory, and by his influence was appointed his assistant, and eventually, in 1822, became his successor. Thence he was promoted in 1825 to Berlin, where he superintended the building of the new observatory, so actively promoted by Humboldt, and remained at its head until within some eighteen months of his death in August, 1865.

On the 26th of November, 1818, Pons of Marseilles discovered a comet, whose inconspicuous appearance gave little promise of its becoming one of the most interesting objects in our system. Encke at once took the calculation of its elements in hand, and brought out the unexpected result that it revolved round the sun in a period of about 3-1/3 years.[242] He, moreover, detected its identity with comets seen by Méchain in 1786, by Caroline Herschel in 1795, by Pons, Huth, and Bouvard in 1805, and after six laborious weeks of research into the disturbances experienced by it from the planets during the entire interval since its first ascertained appearance, he fixed May 24, 1822, as the date of its next return to perihelion. Although on that occasion, owing to the position of the earth, invisible in the northern hemisphere, Sir Thomas Brisbane's observatory at Paramatta was fortunately ready equipped for its recapture, which Rümker effected quite close to the spot indicated by Encke's ephemeris.

The importance of this event can be better understood when it is remembered that it was only the second instance of the recognised return of a comet (that of Halley's, sixty-three years previously, having, as already stated, been the first); and that it, moreover, established the existence of a new class of celestial objects, somewhat loosely distinguished as "comets of short period." These bodies (of which about thirty have been found to circulate within the orbit of Saturn) are remarkable as showing certain planetary affinities in the manners of their motions not at all perceptible in the wider travelling members of their order. They revolve, without exception, in the same direction as the planets—from west to east; they exhibit a marked tendency to conform to the zodiacal track which limits planetary excursions north and south; and their paths round the sun, although much more eccentric than the approximately circular planetary orbits, are far less so than the extravagantly long ellipses in which comets comparatively untrained (as it were) in the habits of the solar system ordinarily perform their revolutions.

No *great* comet is of the "planetary" kind. These are, indeed, only by exception visible to the naked eye; they possess extremely feeble tail-producing powers, and give small signs of central condensation. Thin wisps of cosmical cloud, they flit across the telescopic field of view without sensibly obscuring the smallest star. Their appearance, in short, suggests—what some notable facts in their history will presently be shown to confirm—that they are bodies already effete, and verging towards dissolution. If it be asked what possible connection can be shown to exist between the shortness of period by which they are essentially characterised, and what we may call their *superannuated* condition, we are not altogether at a loss for an answer. Kepler's remark,[243] that comets are consumed by their own emissions, has undoubtedly a measure of truth in it. The substance ejected into the tail must, in overwhelmingly large proportion, be for ever lost to the central mass from which it issues. True, it is of a nature inconceivably tenuous; but unrepaired waste, however small in amount, cannot be persisted in with impunity. The incitement to such self-spoliation proceeds from the sun; it accordingly progresses more rapidly the more numerous are the returns to the solar vicinity. Comets of short period may thus reasonably be expected to *wear out* quickly.

They are, moreover, subject to many adventures and vicissitudes. Their aphelia—or the farthest points of their orbits from the sun—are usually, if not invariably, situated so near to the path either of Jupiter or of Saturn, as to permit these giant planets to act as secondary rulers of their destinies. By their influence they were, in all likelihood, originally fixed in their present tracks; and by their influence, exerted in an opposite sense, they may, in some cases, be eventually ejected from them. Careers so varied, as can easily be imagined, are apt to prove instructive, and astronomers have not been backward in extracting from them the lessons they are fitted to convey. Encke's comet, above all, has served as an index to much curious information, and it may be hoped that its function in that respect is by no means at an end. The great extent of the solar system traversed by its eccentric path makes it peculiarly useful for the determination of the planetary masses. At perihelion it penetrates within the orbit of Mercury; it considerably transcends at aphelion the farthest excursion of Pallas. Its vicinity to the former planet in August, 1835, offered the first convenient opportunity of placing that body in the astronomical balance. Its weight or mass had previously been assumed, not ascertained; and the comparatively slight deviation from its regular course impressed upon the comet by its attractive power showed that it had been assumed nearly twice too great.[244] That fundamental datum of planetary astronomy—the mass of Jupiter—was corrected by similar means; and it was reassuring to find the correction in satisfactory accord with that already introduced from observations of the asteroidal movements.

The fact that comets contract in approaching the sun had been noticed by Hevelius; Pingré admitted it with hesitating perplexity;[245] the example of Encke's comet rendered it conspicuous and undeniable. On the 28th of October, 1828, the diameter of the nebulous matter composing this body was estimated at 312,000 miles. It was then about one and a half times further from the sun than the earth is at the time of the equinox. On the 24th of December following, its distance being reduced by nearly two-thirds, it was found to be only 14,000 miles across.[246] That is to say, it had shrunk during those two months of approach to 1/11000th part of its original volume! Yet it had still seventeen days' journey to make before reaching perihelion. The same curious circumstance was even more markedly apparent at its return in 1838. Its bulk, or the actual space occupied by it, appeared to be reduced, as it drew near the hearth of our system, in the enormous proportion of 800,000 to 1. A corresponding expansion accompanied on each occasion its retirement from the sphere of observation. Similar changes of volume, though rarely to the same astounding extent, have been perceived in other comets. They still remain unexplained; but it can scarcely be doubted that they are due to the action of the same energetic internal forces which reveal themselves in so many splendid and surprising cometary phenomena.

Another question of singular interest was raised by Encke's acute inquiries into the movements and disturbances of the first known "comet of short period." He found from the first that its revolutions were subject to some influence besides that of gravity. After every possible allowance had been made for the pulls, now backward, now forward, exerted upon it by the several planets, there was still a surplus of acceleration left unaccounted for. Each return to perihelion took place about two and a half hours sooner than received theories warranted. Here, then, was a "residual phenomenon" of the utmost promise for the disclosure of novel truths. Encke (in accordance with the opinion of Olbers) explained it as due to the presence in space of some such "subtle matter" as was long ago invoked by Euler[247] to be the agent of eventual destruction for the fair scheme of planetary creation. The apparent anomaly of accounting for an accelerative effect by a retarding cause disappears when it is considered that any check to the motion of bodies revolving round a centre of attraction causes them to draw closer to it, thus shortening their periods and quickening their circulation. If space were filled with a resisting medium capable of impeding, even in the most infinitesimal degree, the swift course of the planets, their orbits should necessarily be, not ellipses, but very close elliptical spirals along which they would slowly, but inevitably, descend into the burning lap of the sun. The circumstance that no such tendency can be traced in their revolutions by no means sets the question at rest. For it might well be that an effect totally imperceptible until after the lapse of countless ages, as regards the solid orbs of our system, might be obvious in the movements of bodies like comets of small mass and great bulk; just as a feather or a gauze veil at once yields its motion to the resistance of the air, while a cannon-ball cuts its way through with comparatively slight loss of velocity.

It will thus be seen that issues of the most momentous character hang on the *time-keeping* of comets; for plainly all must in some degree suffer the same kind of hindrance as Encke's, if the cause of that hindrance be the one suggested. None of its congeners, however, show any trace of similar symptoms. True, the late Professor Oppolzer announced,[248] in 1880, that a comet, first seen by Pons in 1819, and rediscovered by Winnecke in 1858, having a period of 2,052 days (5·6 years), was accelerated at each revolution precisely in the manner required by Encke's theory. But M. von Haerdtl's subsequent investigation, the materials for which included numerous observations of the body in question at its return to the sun in 1886, decisively negatived the presence of any such effect.[249] Moreover, the researches of Von Asten and Backlund[250] into the movements of Encke's comet revealed a perplexing circumstance. They confirmed Encke's results for the period covered by them, but exhibited the acceleration as having *suddenly diminished* by nearly one-half in 1868. The reality and permanence of this change were fully established by observations of the ensuing return in March, 1885. Some physical alteration of the retarded body seems indicated; but visual evidence countenances no such assumption. In aspect the comet is no less thin and diffuse than in 1795 or in 1848.

The character of the supposed resistance in inter-planetary space has, it may be remarked, been often misapprehended. What Encke stipulated for was not a medium equally diffused throughout the visible universe, such as the ethereal vehicle of the vibrations of light, but a rare fluid, rapidly increasing in density towards the sun.[251] This cannot be a solar atmosphere, since it is mathematically certain, as Laplace has shown,[252] that no envelope partaking of the sun's axial rotation can extend farther from his surface than nine-tenths of the mean distance of Mercury; while physical evidence assures us that the *actual* depth of the solar atmosphere bears a very minute proportion to the *possible* depth theoretically assigned to it. That matter, however, not atmospheric in its nature—that is, neither forming one body with the sun nor altogether aëriform—exists in its neighbourhood, can admit of no reasonable doubt. The great lens-shaped mass of the zodiacal light, stretching out at times far beyond the earth's orbit, may indeed be regarded as an extension of the corona, the streamers of which themselves mark the wide diffusion, all round the solar globe, of granular or gaseous materials. Yet comets have been known to penetrate the sphere occupied by them without perceptible loss of velocity. The hypothesis, then, of a resisting medium receives at present no countenance from the movements of comets, whether of short or of long periods.

Although Encke's comet has made thirty-five complete rounds of its orbit since its first detection in 1786, it shows no certain signs of decay. Variations in its brightness are, it is true, conspicuous, but they do not proceed continuously.[253]

The history of the next known planet-like comet has proved of even more curious interest than that of the first. It was discovered by an Austrian officer named Wilhelm von Biela at Josephstadt in Bohemia, February 27, 1826, and ten days later by the French astronomer Gambart at Marseilles. Both observers computed its orbit, showed its remarkable similarity to that traversed by comets visible in 1772 and 1805, and connected them together as previous appearances of the body just detected by assigning to its revolutions a period of between six and seven years. The two brief letters conveying these strikingly similar inferences were printed side by side in the same number of the *Astronomische Nachrichten* (No. 94); but Biela's priority in the discovery of the comet was justly recognised by the bestowal upon it of his name.

The object in question was at no time, subsequently to 1805, visible to the naked eye. Its aspect in Sir John Herschel's great reflector on the 23rd of September, 1832, was described by him as that of a "conspicuous nebula," nearly 3 minutes in diameter. No trace of a tail was discernible. While he was engaged in watching it, a small knot of minute stars was directly traversed by it, "and when on the cluster," he tells us,[254] it "presented the appearance of a nebula resolvable and partly resolved into stars, the stars of the cluster being visible through the comet." Yet the depth of cometary matter through which such faint stellar rays penetrated undimmed, was, near the central parts of the globe, not less than 50,000 miles.

It is curious to find that this seemingly harmless, and we may perhaps add effete body, gave occasion to the first (and not the last) cometary "scare" of an enlightened century. Its orbit, at the descending node, may be said to have intersected that of the earth; since, according as it *bulged in or out* under the disturbing influence of the planets, the passage of the comet was affected *inside* or *outside* the terrestrial track. Now, certain calculations published by Olbers in 1828[255] showed that, on October 29, 1832, a considerable portion of its nebulous surroundings would actually sweep over the spot which, a month later, would be occupied by our planet. It needed no more to set the popular imagination in a ferment. Astronomers, after all, could not, by an alarmed public, be held to be infallible. Their computations, it was averred, which a trifling oversight would suffice to vitiate, exhibited clearly enough the danger, but afforded no guarantee of safety from a collision, with all the terrific consequences frigidly enumerated by Laplace. Nor did the panic subside until Arago formally demonstrated that the earth and the comet could by no possibility approach within less than fifty millions of miles.[256]

The return of the same body in 1845-46 was marked by an extraordinary circumstance. When first seen, November 28, it wore its usual aspect of a faint round patch of cosmical fog; but on December 19, Mr. Hind noticed that it had become distorted somewhat into the form of a pear; and ten days later, it had divided into two separate objects. This singular duplication was first perceived at New Haven in America, December 29,[257] by Messrs. Herrick and Bradley, and by Lieutenant Maury at Washington, January 13, 1846. The earliest British observer of the phenomenon (noticed by Wichmann the same evening at Königsberg) was Professor Challis. "I see *two* comets!" he exclaimed, putting his eye to the great equatoreal of the Cambridge Observatory on the night of January 15; then, distrustful of what his senses had told him, he called in his judgment to correct their improbable report by resolving one of the dubious objects into a hazy star.[258] On the 23rd, however, both were again seen by him in unmistakable cometary shape, and until far on in March (Otto Struve caught a final glimpse of the pair on the 16th of April),[259] continued to be watched with equal curiosity and amazement by astronomers in every part of the northern hemisphere. What Seneca reproved Ephorus for supposing to have taken place in 373 B.C.—what Pingré blamed Kepler for conjecturing in 1618—had then actually occurred under the attentive eyes of science in the middle of the nineteenth century!

At a distance from each other of about two-thirds the distance of the moon from the earth, the twin comets meantime moved on tranquilly, so far, at least, as their course through the heaven was concerned. Their extreme *lightness*, or the small amount of matter contained in each, could not have received a more signal illustration than by the fact that their revolutions round the sun were performed independently; that is to say, they travelled side by side without experiencing any appreciable mutual disturbance, thus plainly showing that at an interval of only 157,250 miles their attractive power was virtually inoperative. Signs of internal agitation, however, were not wanting. Each fragment threw out a short tail in a direction perpendicular to the line joining their centres, and each developed a bright nucleus, although the original comet had exhibited neither of these signs of cometary vitality. A singular interchange of brilliancy was, besides, observed to take place between the coupled objects, each of which alternately outshone and was outshone by the other, while an arc of light, apparently proceeding from the more lustrous, at times bridged the intervening space. Obviously, the gravitational tie, rendered powerless by exiguity of matter, was here replaced by some other form of mutual action, the nature of which can as yet be dealt with only by conjecture.

Once more, in August, 1852, the double comet returned to the neighbourhood of the sun, but under circumstances not the most advantageous for observation. Indeed, the companion was not detected until September 16, when Father Secchi at Rome perceived it to have increased its distance from the originating body to a million and a quarter of miles, or about eight times the average interval at the former appearance. Both vanished shortly afterwards, and have never since been seen, notwithstanding the eager watch kept for objects of such singular interest, and the accurate knowledge of their track supplied by Santini's investigations. A dangerously near approach to Jupiter in 1841 is believed to have occasioned their disruption, and the disaggregating process thus started was likely to continue. We can scarcely doubt that the fate has overtaken them which Newton assigned as the end of all cometary existence. *Diffundi tandem et spargi per cœlos universos.*[260]

Biela's is not the only vanished comet. Brorsen's, discovered at Kiel in 1846, and observed at four subsequent returns, failed unaccountably to become visible in 1890.[261] Yet numerous sentinels were on the alert to surprise its approach along a well-ascertained track, traversed in five and a half years. The object presented from the first a somewhat time-worn aspect. It was devoid of tail, or any other kind of appendage; and the rapid loss of the light acquired during perihelion passage was accompanied by inordinate expansion of an already tenuous globular mass. Another lost or mislaid comet is one found by De Vico at Rome, August 22, 1844. It was expected to return early in 1850, but did not, and has never since been seen; unless its re-appearance as E. Swift's comet of 1894 should be ratified by closer inquiry.[262]

A telescopic comet with a period of 7-1/2 years, discovered November 22, 1843, by M. Faye of the Paris Observatory, formed the subject of a characteristically patient and profound inquiry on the part of Leverrier, designed to test its suggested identity with Lexell's comet of 1770. The result was decisive against the hypothesis of Valz, the divergences between the orbits of the two bodies being found to increase instead of to diminish, as the history of the new-comer was traced backward into the previous century.[263] Faye's comet pursues the most nearly circular path of any similar known object; even at its nearest approach to the sun it remains farther off than Mars when he is most distant from it; and it was proved by the admirable researches of Professor Axel Möller,[264] director of the Swedish observatory of Lund, to exhibit no trace of the action of a resisting medium.

Periodical comets are evidently bodies which have each lived through a chapter of accidents, and a significant hint as to the nature of their adventures can be gathered from the fact that their aphelia are pretty closely grouped about the tracks of the major planets.

Halley's, and five other comets are thus related to Neptune; three connect themselves with Uranus, two with Saturn, above a score with Jupiter. Some form of dependence is plainly indicated, and the researches of Tisserand,[265] Callandreau,[266] and Newton[267] of Yale College, leave scarcely a doubt that the "capture-theory" represents the essential truth in the matter. The original parabolic paths of these comets were then changed into ellipses by the backward pull of a planet, whose sphere of attraction they chanced to enter when approaching the sun from outer space. Moreover, since a body thus affected should necessarily return at each revolution to the scene of encounter, the same process of retardation may, in some cases, have been repeated many times, until the more restricted cometary orbits were reduced to their present dimensions. The prevalence, too, among periodical comets, of direct motion, is shown to be inevitable by M. Callandreau's demonstration that those travelling in a retrograde direction would, by planetary action, be thrown outside the probable range of terrestrial observation. The scarcity of hyperbolic comets can be similarly explained. They would be created whenever the attractive influence of the disturbing planet was exerted in a forward or accelerative sense, but could come only by a rare exception to our notice. The inner planets, including the earth, have also unquestionably played their parts in modifying cometary orbits; and Mr. Plummer suggests, with some show of reason, that the capture of Encke's comet may be a feat due to Mercury.[268]

No *great* comet appeared between the "star" which presided at the birth of Napoleon and the "vintage" comet of 1811. The latter was first described by Flaugergues at Viviers, March 26, 1811; Wisniewski, at Neu-Tscherkask in Southern Russia, caught a final glimpse of it, August 17, 1812. Two disappearances in the solar rays as the earth moved round in its orbit, and two reappearances after conjunction, were included in this unprecedentedly long period of visibility of 510 days. This relative permanence (so far as the inhabitants of Europe were concerned) was due to the high northern latitude attained near perihelion, combined with a certain leisureliness of movement along a path everywhere external to that of the earth. The magnificent luminous train of this body, on October 15, the day of its nearest terrestrial approach, covered an arc of the heavens 23-1/2 degrees in length, corresponding to a real extension of one hundred millions of miles. Its form was described by Sir William Herschel as that of "an inverted hollow cone," and its colour as yellowish, strongly contrasted with the bluish-green tint of the "head," round which it was flung like a transparent veil. The planetary disc of the head, 127,000 miles across, appeared to be composed of strongly-condensed nebulous matter; but somewhat eccentrically situated within it was a star-like nucleus of a reddish tinge, which Herschel presumed to be solid, and ascertained, with his usual care, to have a diameter of 428 miles. From the total absence of phases, as well as from the vivacity of its radiance, he confidently inferred that its light was not borrowed, but inherent.[269]

This remarkable apparition formed the subject of a memoir by Olbers,[270] the striking yet steadily reasoned out suggestions contained in which there was at that time no means of following up with profit. Only of late has the “electrical theory,” of which Zöllner[271] regarded Olbers as the founder, assumed a definite and measurable form, capable of being tested by the touchstone of fact, as knowledge makes its slow inroads on the fundamental mystery of the physical universe.

The paraboloidal shape of the bright envelope separated by a dark interval from the head of the great comet of 1811, and constituting, as it were, the *root* of its tail, seemed to the astronomer of Bremen to reveal the presence of a double repulsion; the expelled vapours accumulating where the two forces, solar and cometary, balanced each other, and being then swept backwards in a huge train. He accordingly distinguished three classes of these bodies:—First, comets which develop *no* matter subject to solar repulsion. These have no tails, and are probably mere nebulosities, without solid nuclei. Secondly, comets which are acted upon by solar repulsion *only*, and consequently throw out no emanations *towards* the sun. Of this kind was a bright comet visible in 1807.[272] Thirdly, comets like that of 1811, giving evidence of action of both kinds. These are distinguished by a dark *hoop* encompassing the head and dividing it from the luminous envelope, as well as by an obscure caudal axis, resulting from the hollow, cone-like structure of the tail.

Again, the ingenious view subsequently propounded by M. Brédikhine as to the connection between the *form* of these appendages and the *kind* of matter composing them, was very clearly anticipated by Olbers. The amount of tail-curvature, he pointed out, depends in each case upon the proportion borne by the velocity of the ascending particles to that of the comet in its orbit; the swifter the outrush, the straighter the resulting tail. But the velocity of the ascending particles varies with the energy of their repulsion by the sun, and this again, it may be presumed, with their quality. Thus multiple tails are developed when the same comet throws off, as it approaches perihelion, specifically distinct substances. The long, straight ray which proceeded from the comet of 1807, for example, was doubtless made up of particles subject to a much more vigorous solar repulsion than those formed into the shorter curved emanation issuing from it nearly in the same direction. In the comet of 1811 he calculated that the particles expelled from the head travelled to the remote extremity of the tail in eleven minutes, indicating by this enormous rapidity of movement (comparable to that of the transmission of light) the action of a force much more powerful than the opposing one of gravity. The not uncommon phenomena of multiple envelopes, on the other hand, he explained as due to the varying amounts of repulsion exercised by the nucleus itself on the different kinds of matter developed from it.

The movements and perturbations of the comet of 1811 were no less profoundly studied by Argelander than its physical constitution by Olbers. The orbit which he assigned to it is of such vast dimensions as to require no less that 3,065 years for the completion of its circuit; and to carry the body describing it at each revolution to fourteen times the distance from the sun of the frigid Neptune. Thus, when it last visited our neighbourhood, Achilles may have gazed on its imposing train as he lay on the sands all night bewailing the loss of

Patroclus; and when it returns, it will perhaps be to shine upon the ruins of empires and civilizations still deep buried among the secrets of the coming time.[273]

On the 26th of June, 1819, while the head of a comet passed across the face of the sun, the earth was in all probability involved in its tail. But of this remarkable double event nothing was known until more than a month later, when the fact of its past occurrence emerged from the calculations of Olbers.[274] Nor had the comet itself been generally visible previous to the first days of July. Several observers, however, on the publication of these results, brought forward accounts of singular spots perceived by them upon the sun at the time of the transit, and an original drawing of one of them, by Pastorff of Buchholtz, has been preserved. This undoubtedly authentic delineation[275] represents a round nebulous object with a *bright* spot in the centre, of decidedly cometary aspect, and not in the least like an ordinary solar "macula." Mr. Hind,[276] nevertheless, showed its position on the sun to be irreconcilable with that which the comet must have occupied; and Mr. Ranyard's discovery of a similar smaller drawing by the same author, dated May 26, 1828,[277] reduces to evanescence the probability of its connection with that body. Indeed, recent experience renders very doubtful the possibility of such an observation.

The return of Halley's comet in 1835 was looked forward to as an opportunity for testing the truth of floating cometary theories, and did not altogether disappoint expectation. As early as 1817, its movements and disturbances since 1759 were proposed by the Turin Academy of Sciences as the subject of a prize ultimately awarded to Baron Damoiseau. Pontécoulant was adjudged a similar distinction by the Paris Academy in 1829; while Rosenberger's calculations were rewarded with the gold medal of the Royal Astronomical Society.[278]

They were verified by the detection at Rome, August 6, 1835, of a nearly circular misty object not far from the predicted place of the comet. It was not, however, until the middle of September that it began to throw out a tail, which by the 15th of October had attained a length of about 24 degrees (on the 19th, at Madras, it extended to fully 30),[279] the head showing to the naked eye as a reddish star rather brighter than Aldebaran or Antares.[280] Some curious phenomena accompanied the process of tail-formation. An outrush of luminous matter, resembling in shape a partially opened fan, issued from the nucleus *towards* the sun, and at a certain point, like smoke driven before a high wind, was vehemently swept backwards in a prolonged train. The appearance of the comet at this time was compared by Bessel,[281] who watched it with minute attention, to that of a blazing rocket. He made the singular observation that this fan of light, which seemed the source of supply for the tail, oscillated like a pendulum to and fro across a line joining the sun and nucleus, in a period of 4-3/5 days; and he was unable to escape from the conclusion[282] that a repulsive force, about twice as powerful as the attractive force of gravity, was concerned in the production of these remarkable effects. Nor did he hesitate to recur to the analogy of magnetic polarity, or to declare, still more emphatically than

Olbers, "the emission of the tail to be a purely electrical phenomenon."[283]

The transformations undergone by this body were almost as strange and complete as those which affected the brigands in Dante's *Inferno*. When first seen, it wore the aspect of a nebula; later it put on the distinctive garb of a comet; it next appeared as a star; finally, it dilated, first in a spherical, then in a paraboloidal form, until May 5, 1836, when it vanished from Herschel's observation at Feldhausen as if by melting into adjacent space from the excessive diffusion of its light. A very uncommon circumstance in its development was that it lost all trace of tail *previous* to its arrival at perihelion on the 16th of November. Nor did it begin to recover its elongated shape for more than two months afterwards. On the 23rd of January, Boguslawski perceived it as a star of the sixth magnitude, *without measurable disc*.[284] Only two nights later, Maclear, director of the Cape Observatory, found the head to be 131 seconds across.[285] And so rapidly did the augmentation of size progress, that Sir John Herschel estimated the actual bulk of this singular object to have increased forty-fold in the ensuing week. "I can hardly doubt," he remarks, "that the comet was fairly evaporated in perihelio by the heat, and resolved into transparent vapour, and is now in process of rapid condensation and re-precipitation on the nucleus."[286] A plausible, but no longer admissible, interpretation of this still unexplained phenomenon. The next return of this body, which will be considerably accelerated by Jupiter's influence, is expected to take place in 1910.[287]

By means of an instrument devised to test the quality of light, Arago obtained decisive evidence that some at least of the radiance proceeding from Halley's comet was derived by reflection from the sun.[288] Indications of the same kind had been afforded[289] by the comet which suddenly appeared above the north-western horizon of Paris, July 3, 1819, after having enveloped (as already stated) our terrestrial abode in its filmy appendages; but the "polariscope" had not then reached the perfection subsequently given to it, and its testimony was accordingly far less reliable than in 1835. Such experiments, however, are in reality more beautiful and ingenious than instructive, since ignited as well as obscure bodies possess the power of throwing back light incident upon them, and will consequently transmit to us from the neighbourhood of the sun rays partly direct, partly reflected, of which a certain proportion will exhibit the peculiarity known as polarisation.

The most brilliant comets of the century were suddenly rivalled if not surpassed by the extraordinary object which blazed out beside the sun, February 28, 1843. It was simultaneously perceived in Mexico and the United States, in Southern Europe, and at sea off the Cape of Good Hope, where the passengers on board the *Owen Glendower* were amazed by the sight of a "short, dagger-like object," closely following the sun towards the western horizon.[290] At Florence, Amici found its distance from the sun's centre at noon to be only 1° 23′; and spectators at Parma were able, when sheltered from the direct glare of mid-day, to trace the tail to a length of four or five degrees. The full dimensions of this astonishing appurtenance began to be disclosed a few days later. On the 3rd of March it measured 25°, and on the 11th, at Calcutta, Mr. Clerihew observed a second streamer, nearly twice as long as the first, and making an angle with it of 18°, to have been emitted in a single day. This rapidity of projection, Sir John Herschel remarked, "conveys an astounding impression of the intensity of the forces at work." "It is clear," he continued, "that *if we have to deal here with matter, such as we conceive it*—viz., *possessing inertia—at all*, it must be under the dominion of forces incomparably more energetic than gravitation, and quite of a different nature."[291]

On the 17th of March a silvery ray, some 40° long and slightly curved at its extremity, shone out above the sunset clouds in this country. No previous intimation had been received of the possibility of such an apparition, and even astronomers—no lightning messages across the seas being as yet possible—were perplexed. The nature of the phenomenon, indeed, soon became evident, but the wonder of it did not diminish with the study of its attendant circumstances. Never before, within astronomical memory, had our system been traversed by a body pursuing such an adventurous career. The closest analogy was offered by the great comet of 1680 (Newton's), which rushed past the sun at a distance of only 144,000 miles; but even this—on the cosmical scale—scarcely perceptible interval was reduced nearly one-half in the case we are now concerned with. The centre of the comet of 1843 approached the formidable luminary within 78,000 miles, leaving, it is estimated, a clear space of not more than 32,000 between the surfaces of the bodies brought into such perilous proximity. The escape of the wanderer was, however, secured by the extraordinary rapidity of its flight. It swept past perihelion at a rate—366 miles a second—which, if continued, would have carried it right round the sun in *two hours*; and in only eleven minutes more than that short period it actually described half the *curvature* of its orbit—an arc of 180°—although in travelling over the remaining half many hundreds of sluggish years will doubtless be consumed.

The behaviour of this comet may be regarded as an *experimentum crucis* as to the nature of tails. For clearly no fixed appendage many millions of miles in length could be whirled like a brandished sabre from one side of the sun to the other in 131 minutes. Cometary trains are then, as Olbers rightly conceived them to be, emanations, not appendages—inconceivably rapid outflows of highly rarefied matter, the greater part, if not all, of which becomes permanently detached from the nucleus.

That of the comet of 1843 reached, about the time that it became visible in this country, the extravagant length of 200 millions of miles.[292] It was narrow, and bounded by nearly parallel and nearly rectilinear lines, resembling—to borrow a comparison of Aristotle's—a "road" through the constellations; and after the 3rd of March showed no trace of hollowness, the axis being, in fact, rather brighter than the edges. Distinctly perceptible in it were those singular aurora-like coruscations which gave to the "tresses" of Charles V.'s comet the appearance—as Cardan described it—of "a torch agitated by the wind," and have not unfrequently been observed to characterise other similar objects. A consideration first adverted to by Olbers proves these to originate in our own atmosphere. For owing to the great difference in the distances from the earth of the origin and extremity of such vast effluxes, the light proceeding from their various parts is transmitted to our eyes in notably different intervals of time. Consequently a luminous undulation, even though propagated instantaneously from end to end of a comet's tail, would appear to us to occupy many minutes in its progress. But the coruscations in question pass as swiftly as a falling star. They are, then, of terrestrial production.

Periods of the utmost variety were by different computators assigned to the body, which arrived at perihelion, February 27, 1843, at 9.47 P.M. Professor Hubbard of Washington found that it required 533 years to complete a revolution; MM. Laugier and Mauvais of Paris considered the true term to be 35;[293] Clausen looked for its return at the end of between six and seven. A recent discussion[294] by Professor Kreutz of all the available data gives a probable period of 512 years for this body, and precludes its hypothetical identity with the comet of 1668, known as the "Spina" of Cassini.

It may now be asked, what were the conclusions regarding the nature of comets drawn by astronomers from the considerable amount of novel experience accumulated during the first half of this century? The first and best assured was that the matter composing them is in a state of extreme tenuity. Numerous and trustworthy observations showed that the feeblest rays of light might traverse some hundreds of thousands of miles of their substance, even where it was apparently most condensed, without being perceptibly weakened. Nay, instances were recorded in which stars were said to have gained in brightness from the process![295] On the 24th of June, 1825, Olbers[296] saw the comet then visible all but obliterated by the central passage of a star too small to be distinguished with the naked eye, its own light remaining wholly unchanged. A similar effect was noted December 1, 1811, when the great comet of that year approached so close to Altair, the *lucida* of the Eagle, that the star seemed to be transformed into the nucleus of the comet.[297] Even the central blaze of Halley's comet in 1835 was powerless to impede the passage of stellar rays. Struve[298] observed at Dorpat, on September 17, an all but central occultation; Glaisher[299] one (so far as he could ascertain) absolutely so eight days later at Cambridge. In neither case was there any appreciable diminution of the star's light. Again, on the 11th of October, 1847, Mr. Dawes,[300] an exceptionally keen observer, distinctly saw a star of the tenth magnitude through the exact centre of a comet discovered on the first of that month by Maria Mitchell of Nantucket.

Examples, on the other hand, are not wanting of the diminution of stellar light under similar circumstances;[301] and we meet two alleged instances of the vanishing of a star behind a comet. Wartmann of Geneva observed the first, November 28, 1828;[302] but his instrument was defective, and the eclipsing body, Encke's comet, has shown itself otherwise perfectly translucent. The second case of occultation occurred September 13, 1890, when an eleventh magnitude star was stated to have completely disappeared during the transit over it of Denning's comet.[303]

From the failure to detect any effects of refraction in the light of stars occulted by comets, it was inferred (though, as we know now, erroneously) that their composition is rather that of dust than that of vapour; that they consist not of any continuous substance, but of discrete solid particles, very finely divided and widely scattered. In conformity with this view was the known smallness of their masses. Laplace had shown that if the amount of matter forming Lexell's comet had been as much as 1/5000 of that contained in our globe, the effect of its attraction, on the occasion of its approach within 1,438,000 miles of the earth, July 1, 1770, must have been apparent in the lengthening of the year. And that some comets, at any rate, possess masses immeasurably below this maximum value was clearly proved by the undisturbed parallel march of the two fragments of Biela's in 1846.

But the discovery in this branch most distinctive of the period under review is that of "short period" comets, of which four[304] were known in 1850. These, by the character of their movements, serve as a link between the planetary and cometary worlds, and by the nature of their construction, seem to mark a stage in cometary decay. For that comets are rather transitory agglomerations, than permanent products of cosmical manufacture, appeared to be demonstrated by the division and disappearance of one amongst their number, as well as by the singular and rapid changes in appearance undergone by many, and the seemingly irrevocable diffusion of their substance visible in nearly all. They might then be defined, according to the ideas respecting them prevalent fifty years ago, as bodies unconnected by origin with the solar system, but encountered, and to some extent appropriated, by it in its progress through space, owing their visibility in great part, if not altogether, to light reflected from the sun, and their singular and striking forms to the action of repulsive forces emanating from him, the penalty of their evanescent splendour being paid in gradual waste and final dissipation and extinction.

FOOTNOTES:

[241] *Allgemeine Geographische Ephemeriden*, vol. iv., p. 287.

[242] *Astr. Jahrbuch*, 1823, p. 217. The period (1,208 days) of this body is considerably shorter than that of any other known comet.

[243] “Sicut bombyces filo fundendo, sic cometas cauda exspiranda consumi et denique mori.”—*De Cometis*, Op., vol. vii., p. 110.

[244] Considerable uncertainty, however, still prevails on the point. The inverse relation assumed by Lagrange to exist between distance from the sun and density brought out the Mercurian mass 1/2025810 that of the sun (Laplace, *Exposition du Syst. du Monde*, t. ii., p. 50, ed. 1824). Von Asten deduced from the movements of Encke’s comet, 1818-48, a value of 1/7636440; while Backlund from its seven returns, 1871-1891, derived 1/9647000 (*Comptes Rendus*, Oct. 1, 1894).

[245] Arago, *Annuaire* (1832), p. 218.

[246] Hind, *The Comets*, p. 20.

[247] *Phil. Trans.*, vol. xlvi., p. 204.

[248] *Astr. Nach.*, No. 2,134.

[249] *Comptes Rendus*, t. cvii., p. 588.

[250] *Mém. de St. Pétersbourg*, t. xxxii., No. 3, 1884; *Astr. Nach.*, No. 2,727.

[251] *Month. Not.*, vol. xix., p. 72.

[252] *Mécanique Céleste*, t. ii., p. 197.

[253] See Berberich, *Astr. Nach.*, Nos. 2,836-7, 3,125; Deichmüller, *Ibid.*, No. 3,123.

[254] *Month. Not.*, vol. ii., p. 117.

[255] *Astr. Nach.*, No. 128.

[256] *Annuaire*, 1832, p. 186.

[257] *Am. Journ. of Science*, vol. i. (2nd series), p. 293. Prof. Hubbard’s calculations indicated a probability that the definitive separation of the two nuclei occurred as early as September 30, 1884. *Astronomical Journal* (Gould’s), vol. iv., p. 5. See also, on the subject of this comet, W. T. Lynn, *Intellectual Observer*, vol. xi., p. 208; E. Ledger, *Observatory*, August, 1883, p. 244; and H. A. Newton, *Am. Journ. of Science*, vol. xxxi., p. 81, February, 1886.

[258] *Month. Not.*, vol. vii., p. 73.

[259] *Bulletin Ac. Imp. de St. Pétersbourg*, t. vi., col. 77. The latest observation of the parent nucleus was that of Argelander, April 27, at Bonn.

[260] D’Arrest, *Astr. Nach.*, No. 1,624.

[261] *Der Brorsen’sche Comet.* Von Dr. E. Lamp, Kiel, 1892; Plummer, *Knowledge*, vol. xix., p. 41.

[262] Schulhof, *Astr. Nach.*, No. 3,267; *Observatory*, vol. xviii., p. 64; F. H. Seares, *Astr. Nach.*, Nos. 3,606-7; Plummer, *Knowledge*, vol. xix., p. 156.

[263] *Comptes Rendus*, t. xxv., p. 570.

[264] *Month. Not.*, vol. xii., p. 248.

[265] *Bull. Astr.*, t. vi., pp. 241, 289.

[266] *Étude sur la Théorie des Comètes périodiques. Annales de l’Observatoíre*, t. xx., Paris, 1891.

[267] *Amer. Journ. of Science*, vol. xlii., pp. 183, 482, 1891.

[268] *Observatory*, vol. xiv., p. 194.

[269] *Phil. Trans.*, vol. cii., pp. 118-124.

[270] *Ueber den Schweif des grossen Cometen von 1811*, *Monat. Corr.*, vol. xxv., pp. 3-22. Reprinted by Zöllner. *Ueber die Natur der Cometen*, pp. 3-15.

[271] *Natur der Cometen*, p. 148.

[272] The subject of a classical memoir by Bessel, published in 1810.

[273] A fresh investigation of its orbit has been published by N. Herz of Vienna. See *Bull. Astr.*, t. ix., p. 427.

[274] *Astr. Jahrbuch* (Bode's), 1823, p. 134.

[275] Reproduced in Webb's *Celestial Objects*, 4th ed.

[276] *Month. Not.*, vol. xxxvi., p. 309.

[277] *Celestial Objects*, p. 40, note.

[278] See Airy's Address, *Mem. R. A. S.*, vol. x., p. 376. Rosenberger calculated no more, though he lived until 1890. W. T. Lynn, *Observatory*, vol. xiii., p. 125.

[279] Hind, *The Comets*, p. 47.

[280] Arago, *Annuaire*, 1836, p. 228.

[281] *Astr. Nach.*, No. 300.

[282] It deserves to be recorded that Robert Hooke drew a very similar inference from his observations of the comets of 1680 and 1682. *Month. Not.*, vol. xiv., pp. 77-83.

[283] *Briefwechsel zwischen Olbers und Bessel*, Bd. ii., p. 390.

[284] Herschel, *Results*, p. 405.

[285] *Mem. R. A. S.*, vol. x., p. 92,

[286] *Results*, p. 401.

[287] Pontécoulant, *Comptes Rendus*, t. lviii., p. 825.

[288] *Annuaire*, 1836, p. 233.

[289] *Cosmos*, vol. i., p. 90, *note* (Otté's trans.).

[290] Herschel, *Outlines of Astronomy*, p. 399, 9th ed.

[291] *Outlines*, p. 398.

[292] Boguslawski calculated that it extended on the 21st of March to 581 millions.—*Report. Brit. Ass.*, 1845, p. 89.

[293] *Comptes Rendus*, t. xvi., p. 919.

[294] *Observatory*, vol. xxiv., p. 167; Astr. Nach., No. 3,320.

[295] Piazzi noticed a considerable increase of lustre in a very faint star of the twelfth magnitude viewed through a comet. Mädler, *Reden*, etc., p. 248, *note*.

[296] *Astr. Jahrbuch*, 1828, p. 151.

[297] Mädler, *Gesch. d. Astr.*, Bd. ii., p. 412.

[298] *Recueil de l'Ac. Imp. de St. Pétersbourg*, 1835, p. 143.

[299] Guillemin's *World of Comets*, trans, by J. Glaisher, p. 294, *note*.

[300] *Month. Not.*, vol. viii., p. 9.

[301] A real, though only partial stoppage of light seems indicated by Herschel's observations on the comet of 1807. Stars seen through the tail, October 18, lost much of their lustre. One near the head was only faintly visible by glimpses. *Phil. Trans.*, vol. xcvii., p. 153.

[302] Arago, *Annuaire*, 1832, p. 205.

[303] *Ibid.*, 1891, p. 290.

[304] Viz., Encke's, Biela's, Faye's, and Brorsen's.

CHAPTER VI

INSTRUMENTAL ADVANCES

It is impossible to follow with intelligent interest the course of astronomical discovery without feeling some curiosity as to the means by which such surpassing results have been secured. Indeed, the bare acquaintance with *what* has been achieved, without any corresponding knowledge of *how* it has been achieved, supplies food for barren wonder rather than for fruitful and profitable thought. Ideas advance most readily along the solid ground of practical reality, and often find true sublimity while laying aside empty marvels. Progress is the result, not so much of sudden flights of genius, as of sustained, patient, often commonplace endeavour; and the true lesson of scientific history lies in the close connection which it discloses between the most brilliant developments of knowledge and the faithful accomplishment of his daily task by each individual thinker and worker.

It would be easy to fill a volume with the detailed account of the long succession of optical and mechanical improvements by means of which the observation of the heavens has been brought to its present degree of perfection; but we must here content ourselves with a summary sketch of the chief amongst them. The first place in our consideration is naturally claimed by the telescope.

This marvellous instrument, we need hardly remind our readers, is of two distinct kinds—that in which light is gathered together into a focus by *refraction*, and that in which the same end is attained by *reflection*. The image formed is in each case viewed through a magnifying lens, or combination of lenses, called the eye-piece. Not for above a century after the “optic glasses” invented or stumbled upon by the spectacle-maker of Middelburg (1608) had become diffused over Europe, did the reflecting telescope come, even in England, the place of its birth, into general use. Its principle (a sufficiently obvious one) had indeed been suggested by Mersenne as early as 1639;[305] James Gregory in 1663[306] described in detail a mode of embodying that principle in a practical shape; and Newton, adopting an original system of construction, actually produced in 1668 a tiny speculum, one inch across, by means of which the apparent distance of objects was reduced thirty-nine times. Nevertheless, the exorbitantly long tubeless refractors, introduced by Huygens, maintained their reputation until Hadley exhibited to the Royal Society, January 12, 1721,[307] a reflector of six inches aperture, and sixty-two in focal length, which rivalled in performance, and of course indefinitely surpassed in manageability, one of the “aerial” kind of 123 feet.

The concave-mirror system now gained a decided ascendant, and was brought to unexampled perfection by James Short of Edinburgh during the years 1732-68. Its resources were, however, first fully developed by William Herschel. The energy and inventiveness of this extraordinary man marked an epoch wherever they were applied. His ardent desire to measure and gauge the stupendous array of worlds which his specula revealed to him, made him continually intent upon adding to their "space-penetrating power" by increasing their light-gathering surface. These, as he was the first to explain, [308] are in a constant proportion one to the other. For a telescope with twice the linear aperture of another will collect four times as much light, and will consequently disclose an object four times as faint as could be seen with the first, or, what comes to the same, an object equally bright at twice the distance. In other words, it will possess double the space-penetrating power of the smaller instrument. Herschel's great mirrors—the first examples of the giant telescopes of modern times—were then primarily engines for extending the bounds of the visible universe; and from the sublimity of this "final cause" was derived the vivid enthusiasm which animated his efforts to success.

It seems probable that the seven-foot telescope constructed by him in 1775—that is within little more than a year after his experiments in shaping and polishing metal had begun—already exceeded in effective power any work by an earlier optician; and both his skill and his ambition rapidly developed. His efforts culminated, after mirrors of ten, twenty, and thirty feet focal length had successively left his hands, in the gigantic forty-foot, completed August 28, 1789. It was the first reflector in which only a single mirror was employed. In the "Gregorian" form, the focussed rays are, by a second reflection from a small concave[309] mirror, thrown *straight back* through a central aperture in the larger one, behind which the eye-piece is fixed. The object under examination is thus seen in the natural direction. The "Newtonian," on the other hand, shows the object in a line of sight at right angles to the true one, the light collected by the speculum being diverted to one side of the tube by the interposition of a small plane mirror, situated at an angle of 45° to the axis of the instrument. Upon these two systems Herschel worked until 1787, when, becoming convinced of the supreme importance of economising light (necessarily wasted by the second reflection), he laid aside the small mirror of his forty-foot then in course of construction, and turned it into a "front-view" reflector. This was done—according to the plan proposed by Lemaire in 1732—by slightly inclining the speculum so as to enable the image formed by it to be viewed with an eye-glass fixed at the upper margin of the tube. The observer thus stood with his back turned to the object he was engaged in scrutinising.

The advantages of the increased brilliancy afforded by this modification were strikingly illustrated by the discovery, August 28 and September 17, 1789, of the two Saturnian satellites nearest the ring. Nevertheless, the monster telescope of Slough cannot be said to have realised the sanguine expectations of its constructor. The occasions on which it could be usefully employed were found to be extremely rare. It was injuriously affected by every change of temperature. The great weight (25 cwt.) of a speculum four feet in diameter rendered it peculiarly liable to distortion. With all imaginable care, the delicate lustre of its surface could not be preserved longer than two years,[310] when the difficult process of repolishing had to be undertaken. It was accordingly never used after 1811, when, having *gone blind* from damp, it lapsed by degrees into the condition of a museum inmate.

The exceedingly high magnifying powers employed by Herschel constituted a novelty in optical astronomy, to which he attached great importance. The work of ordinary observation would, however, be hindered rather than helped by them. The attempt to increase in this manner the efficacy of the telescope is speedily checked by atmospheric, to say nothing of other difficulties. Precisely in the same proportion as an object is magnified, the disturbances of the medium through which it is seen are magnified also. Even on the clearest and most tranquil nights, the air is never for a moment really still. The rays of light traversing it are continually broken by minute fluctuations of refractive power caused by changes of temperature and pressure, and the currents which these engender. With such luminous quiverings and waverings the astronomer has always more or less to reckon; their absence is simply a question of degree; if sufficiently magnified, they are at all times capable of rendering observation impossible.

Thus, such powers as 3,000, 4,000, 5,000, even 6,652,[311] which Herschel now and again applied to his great telescopes, must, save on the rarest occasions, prove an impediment rather than an aid to vision. They were, however, used by him only for special purposes, experimentally, not systematically, and with the clearest discrimination of their advantages and drawbacks. It is obvious that perfectly different ends are subserved by increasing the *aperture* and by increasing the *power* of a telescope. In the one case, a larger quantity of light is captured and concentrated; in the other, the same amount is distributed over a wider area. A diminution of brilliancy in the image accordingly attends, *cæteris paribus*, upon each augmentation of its apparent size. For this reason, such faint objects as nebulæ are most successfully observed with moderate powers applied to instruments of a great capacity for light, the details of their structure actually disappearing when highly magnified. With stellar groups the reverse is the case. Stars cannot be magnified, simply because they are too remote to have any sensible dimensions; but the space between them can. It was thus for the purpose of dividing very close double stars that Herschel increased to such an unprecedented extent the magnifying capabilities of his instruments; and to this improvement incidentally the discovery of Uranus, March 13, 1781,[312] was due. For by the examination with strong lenses of an object which, even with a power of 227, presented a suspicious appearance, he was able at once to pronounce its disc to be real, not merely "spurious," and so to distinguish it unerringly from the crowd of stars amidst which it was moving.

While the reflecting telescope was astonishing the world by its rapid development in the hands of Herschel, its unpretending rival was slowly making its way towards the position which the future had in store for it. The great obstacle which long stood in the way of the improvement of refractors was the defect known as "chromatic aberration." This is due to no other cause than that which produces the rainbow and the spectrum—the separation, or "dispersion" in their passage through a refracting medium, of the variously coloured rays composing a beam of white light. In an ordinary lens there is no common point of concentration; each colour has its own separate focus; and the resulting image, formed by the superposition of as many images as there are hues in the spectrum, is indefinitely terminated with a tinted border, eminently baffling to exactness of observation.

The extravagantly long telescopes of the seventeenth century were designed to *avoid* this evil (as well as another source of indistinct vision in the spherical shape of lenses); but no attempt to *remedy* it was made until an Essex gentleman succeeded, in 1733, in so combining lenses of flint and crown glass as to produce refraction without colour.[313] Mr. Chester More Hall was, however, equally indifferent to fame and profit, and took no pains to make his invention public. The *effective* discovery of the achromatic telescope was, accordingly, reserved for John Dollond, whose method of correcting at the same time chromatic and spherical aberration was laid before the Royal Society in 1758. Modern astronomy may be said to have been thereby rendered possible. Refractors have always been found better suited than reflectors to the ordinary work of observatories. They are, so to speak, of a more robust, as well as of a more plastic nature. They suffer less from vicissitudes of temperature and climate. They retain their efficiency with fewer precautions and under more trying circumstances. Above all, they co-operate more readily with mechanical appliances, and lend themselves with far greater facility to purposes of exact measurement.

A practical difficulty, however, impeded the realisation of the brilliant prospects held out by Dollond's invention. It was found impossible to procure flint-glass, such as was needed for optical use—that is, of perfectly homogeneous quality—except in fragments of insignificant size. Discs of more than two or three inches in diameter were of extreme rarity; and the crushing excise duty imposed upon the article by the financial unwisdom of the Government, both limited its production, and, by rendering experiments too costly for repetition, barred its improvement.

Up to this time, Great Britain had left foreign competitors far behind in the instrumental department of astronomy. The quadrants and circles of Bird, Cary and Ramsden were unapproached abroad. The reflecting telescope came into existence and reached maturity on British soil. The refracting telescope was cured of its inherent vices by British ingenuity. But with the opening of the nineteenth century, the almost unbroken monopoly of skill and contrivance which our countrymen had succeeded in establishing was invaded, and British workmen had to be content to exchange a position of supremacy for one of at least partial temporary inferiority.

Somewhat about the time that Herschel set about polishing his first speculum, Pierre Louis Guinand, a Swiss artisan, living near Chaux-de-Fonds, in the canton of Neuchâtel, began to grind spectacles for his own use, and was thence led on to the rude construction of telescopes by fixing lenses in pasteboard tubes. The sight of an England achromatic stirred a higher ambition, and he took the first opportunity of procuring some flint glass from England (then the only source of supply), with the design of imitating an instrument the full capabilities of which he was destined to be the humble means of developing. The

English glass proving of inferior quality, he conceived the possibility, unaided and ignorant of the art as he was, of himself making better, and spent seven years (1784-90) in fruitless experiments directed to that end. Failure only stimulated him to enlarge their scale. He bought some land near Les Brenets, constructed upon it a furnace capable of melting two quintals of glass, and reducing himself and his family to the barest necessaries of life, he poured his earnings (he at this time made bells for repeaters) unstintingly into his crucibles.[314] His undaunted resolution triumphed. In 1799 he carried to Paris and there showed to Lalande several discs of flawless crystal four to six inches in diameter. Lalande advised him to keep his secret, but in 1805 he was induced to remove to Munich, where he became the instructor of the immortal Fraunhofer. His return to Les Brenets in 1814 was signalised by the discovery of an ingenious mode of removing striated portions of glass by breaking and re-soldering the product of each melting, and he eventually attained to the manufacture of perfect discs up to 18 inches in diameter. An object-glass for which he had furnished the material to Cauchoix, procured him, in 1823, a royal invitation to settle in Paris; but he was no longer equal to the change, and died at the scene of his labours, February 13 following.

This same lens (12 inches across) was afterwards purchased by Sir James South, and the first observation made with it, February 13, 1830, disclosed to Sir John Herschel the sixth minute star in the central group of the Orion nebula, known as the “trapezium.”[315] Bequeathed by South to Trinity College, Dublin, it was employed at the Dunsink Observatory by Brünnow and Ball in their investigations of stellar parallax. A still larger objective (of nearly 14 inches) made of Guinand’s glass was secured in Paris, about the same time, by Mr. Edward Cooper of Markree Castle, Ireland. The peculiarity of the method discovered at Les Brenets resided in the manipulation, not in the quality of the ingredients; the secret, that is to say, was not chemical, but mechanical.[316] It was communicated by Henry Guinand (a son of the inventor) to Bontemps, one of the directors of the glassworks at Choisy-le-Roi, and by him transmitted to Messrs. Chance of Birmingham, with whom he entered into partnership when the revolutionary troubles of 1848 obliged him to quit his native country. The celebrated American opticians, Alvan Clark & Sons, derived from the Birmingham firm the materials for some of their early telescopes, notably the 19-inch Chicago and 26-inch Washington equatoreals; but the discs for the great Lick refractor, and others shaped by them in recent years, have been supplied by Feil of Paris.

Two distinguished amateurs, meanwhile, were preparing to reassert on behalf of reflecting instruments their claim to the place of honour in the van of astronomical discovery. Of Mr. Lassell’s specula something has already been said.[317] They were composed of an alloy of copper and tin, with a minute proportion of arsenic (after the example of Newton[318]), and were remarkable for perfection of figure and brilliancy of surface.

The capabilities of the Newtonian plan were developed still more fully—it might almost be said to the uttermost—by the enterprise of an Irish nobleman. William Parsons, known as Lord Oxmantown until 1841, when, on his father's death, he succeeded to the title of Earl of Rosse, was born at York, June 17, 1800. His public duties began before his education was completed. He was returned to Parliament as member for King's County while still an undergraduate at Oxford, and continued to represent the same constituency for thirteen years (1821-34). From 1845 until his death, which took place, October 31, 1867, he sat, silent but assiduous, in the House of Lords as an Irish representative peer; he held the not unlaborious post of President of the Royal Society from 1849 to 1854; presided over the meeting of the British Association at Cork in 1843, and was elected Vice-Chancellor of Dublin University in 1862. In addition to these extensive demands upon his time and thoughts, were those derived from his position as practically the feudal chief of a large body of tenantry in times of great and anxious responsibility, to say nothing of the more genial claims of an unstinted hospitality. Yet, while neglecting no public or private duty, this model nobleman found leisure to render to science services so conspicuous as to entitle his name to a lasting place in its annals. He early formed the design of reaching the limits of the attainable in enlarging the powers of the telescope, and the qualities of his mind conspired with the circumstances of his fortune to render the design a feasible one. From refractors it was obvious that no such vast and rapid advance could be expected. English glass-manufacture was still in a backward state. So late as 1839, Simms (successor to the distinguished instrumentalist Edward Troughton) reported a specimen of crystal scarcely 7-1/2 inches in diameter, and perfect only over six, to be unique in the history of English glass-making.[319] Yet at that time the fifteen-inch achromatic of Pulkowa had already left the workshop of Fraunhofer's successors at Munich. It was not indeed until 1845, when the impost which had so long hampered their efforts was removed, that the optical artists of these islands were able to compete on equal terms with their rivals on the Continent. In the case of reflectors, however, there seemed no insurmountable obstacle to an almost unlimited increase of light-gathering capacity; and it was here, after some unproductive experiments with fluid lenses, that Lord Oxmantown concentrated his energies.

He had to rely entirely on his own invention, and to earn his own experience. James Short had solved the problem of giving to metallic surfaces a perfect parabolic figure (the only one by which parallel incident rays can be brought to an exact focus); but so jealous was he of his secret, that he caused all his tools to be burnt before his death;[320] nor was anything known of the processes by which Herschel had achieved his astonishing results. Moreover, Lord Oxmantown had no skilled workmen to assist him. His implements, both animate and inanimate, had to be formed by himself. Peasants taken from the plough were educated by him into efficient mechanics and engineers. The delicate and complex machinery needed in operations of such hairbreadth nicety as his enterprise involved, the steam-engine which was to set it in motion, at times the very crucibles in which his specula were cast, issued from his own workshops.

In 1827 experiments on the composition of speculum-metal were set on foot, and the first polishing-machine ever driven by steam-power was contrived in 1828. But twelve arduous years of struggle with recurring difficulties passed before success began to dawn. A material less tractable than the alloy selected, of four chemical equivalents of copper to one of tin,[321] can scarcely be conceived. It is harder than steel, yet brittle as glass, crumbling into fragments with the slightest inadvertence of handling or treatment;[322] and the precision of figure requisite to secure good definition is almost beyond the power of language to convey. The quantities involved are so small as not alone to elude sight, but to confound imagination. Sir John Herschel tells us that "the *total* thickness to be abraded from the edge of a spherical speculum 48 inches in diameter and 40 feet focus, to convert it into a paraboloid, is only 1/21333 of an inch;"[323] yet upon this minute difference of form depends the clearness of the image, and, as a consequence, the entire efficiency of the instrument. "Almost infinite," indeed (in the phrase of the late Dr. Robinson), must be the exactitude of the operation adapted to bring about so delicate a result.

At length, in 1839, two specula, each three feet in diameter, were turned out in such perfection as to prompt a still bolder experiment. The various processes needed to insure success were now ascertained and under control; all that was necessary was to repeat them on a larger scale. A gigantic mirror, six feet across and fifty-four in focal length, was accordingly cast on the 13th of April, 1842; in two months it was ground down to figure by abrasion with emery and water, and daintily polished with rouge; and by the month of February, 1845, the "leviathan of Parsonstown" was available for the examination of the heavens.

The suitable mounting of this vast machine was a problem scarcely less difficult than its construction. The shape of a speculum needs to be maintained with an elaborate care equal to that used in imparting it. In fact, one of the most formidable obstacles to increasing the size of such reflecting surfaces consists in their liability to bend under their own weight. That of the great Rosse speculum was no less than four tons. Yet, although six inches in thickness, and composed of a material only a degree inferior in rigidity to wrought iron, the strong pressure of a man's hand at its back produced sufficient flexure to distort perceptibly the image of a star reflected in it.[324] Thus the delicacy of its form was perishable equally by the stress of its own gravity, and by the slightest irregularity in the means taken to counteract that stress. The problem of affording a perfectly equable support in all possible positions was solved by resting the speculum upon twenty-seven platforms of cast iron, felt-covered, and carefully fitted to the shape of the areas they were to carry, which platforms were themselves borne by a complex system of triangles and levers, ingeniously adapted to distribute the weight with complete uniformity.[325]

A tube which resembled, when erect, one of the ancient round towers of Ireland,[326] served as the habitation of the great mirror. It was constructed of deal staves bound together with iron hoops, was fifty-eight feet long (including the speculum-box), and seven in diameter. A reasonably tall man may walk through it (as Dean Peacock once did) with umbrella uplifted. Two piers of solid masonry, about fifty feet high, seventy long, and twenty-three apart, flanked the huge engine on either side. Its lower extremity rested on a universal joint of cast iron; above, it was slung in chains, and even in a gale of wind remained perfectly steady. The weight of the entire, although amounting to fifteen tons, was so skilfully counterpoised, that the tube could with ease be raised or depressed by two men working a windlass. Its horizontal range was limited by the lofty walls erected for its support to about ten degrees on each side of the meridian; but it moved vertically from near the horizon through the zenith as far as the pole. Its construction was of the Newtonian kind, the observer looking into the side of the tube near its upper end, which a series of galleries and sliding stages enabled him to reach in any position. It has also, though rarely, been used without a second mirror, as a "Herschelian" reflector.

The splendour of the celestial objects as viewed with this vast "light-grasper" surpassed all expectation. "Never in my life," exclaimed Sir James South, "did I see such glorious sidereal pictures."[327] The orb of Jupiter produced an effect compared to that of the introduction of a coach-lamp into the telescope;[328] and certain star-clusters exhibited an appearance (we again quote Sir James South) "such as man before had never seen, and which for its magnificence baffles all description." But it was in the examination of the nebulæ that the superiority of the new instrument was most strikingly displayed. A large number of these misty objects, which the utmost powers of Herschel's specula had failed to resolve into stars, yielded at once to the Parsonstown reflector; while many others showed under entirely changed forms through the disclosure of previously unseen details of structure.

One extremely curious result of the increase of light was the abolition of any sharp distinction between the two classes of "annular" and "planetary" nebulæ. Up to that time, only four ring-shaped systems—two in the northern and two in the southern hemisphere—were known to astronomers; they were now reinforced by five of the planetary kind, the discs of which were observed to be centrally perforated; while the definite margins visible in weaker instruments were replaced by ragged edges or filamentous fringes.

Still more striking was the discovery of an entirely new and most remarkable species of nebulæ. These were termed "spiral," from the more or less regular convolutions, resembling the whorls of a shell, in which the matter composing them appeared to be distributed. The first and most conspicuous specimen of this class was met with in April, 1845; it is situated in Canes Venatici, close to the tail of the Great Bear, and wore, in Sir J. Herschel's instruments, the aspect of a split ring encompassing a bright nucleus, thus presenting, as he supposed, a complete analogue to the system of the Milky Way. In the Rosse mirror it shone out as a vast whirlpool of light—a stupendous witness to the presence of cosmical activities on the grandest scale, yet regulated by laws as to the nature of which we are profoundly ignorant. Professor Stephen Alexander of New Jersey, however, concluded, from an investigation (necessarily founded on highly precarious data) of the mechanical condition of these extraordinary agglomerations, that we see in them "the partially scattered fragments of enormous masses once rotating in a state of dynamical equilibrium." He further suggested "that the separation of these fragments may still be in progress,"[329] and traced back their origin to the disruption, through its own continually accelerated rotation, of a "primitive spheroid" of inconceivably vast dimensions. Such also, it was added (the curvilinear form of certain outliers of the Milky Way giving evidence of a spiral structure), is probably the history of our own cluster; the stars composing which, no longer held together in a delicately adjusted system like that of the sun and planets, are advancing through a period of seeming confusion towards an appointed goal of higher order and more perfect and harmonious adaptation.[330]

The class of spiral nebulæ included, in 1850, fourteen members, besides several in which the characteristic arrangement seemed partial or dubious.[331] A tendency in the exterior stars of other clusters to gather into curved branches (as in our Galaxy) was likewise noted; and the existence of unsuspected analogies was proclaimed by the significant combination in the "Owl" nebula (a large planetary in Ursa Major)[332] of the twisted forms of a spiral with the perforated effect distinctive of an annular nebula. Once more, by the achievements of the Parsonstown reflector, the supposition of a "shining fluid" filling vast regions of space was brought into (as it has since proved) undeserved discredit. Although Lord Rosse himself rejected the inference, that because many nebulæ had been resolved, all were resolvable, very few imitated his truly scientific caution; and the results of Bond's investigations[333] with the Harvard College refractor quickened and strengthened the current of prevalent opinion. It is now certain that the evidence furnished on both sides of the Atlantic as to the stellar composition of some conspicuous objects of this class (notably the Orion and "Dumb-bell" nebulæ) was delusive; but the spectroscope alone was capable of meeting it with a categorical denial. Meanwhile there seemed good ground for the persuasion, which now, for the last time, gained the upper hand, that nebulæ are, without exception, true "island-universes," or assemblages of distant suns.

Lord Rosse's telescope possesses a nominal power of 6,000—that is, it shows the moon as if viewed with the naked eye at a distance of forty miles. But this seeming advantage is neutralised by the weakening of the available light through excessive diffusion, as well as by the troubles of the surging sea of air through which the observation must necessarily be made. Professor Newcomb, in fact, doubts whether with *any* telescope our satellite has ever been seen to such advantage as it would be if brought within 500 miles of the unarmed eye.[334]

The French opticians' rule of doubling the number of millimetres contained in the aperture of an instrument to find the highest magnifying power usually applicable to it, would give 3,600 as the maximum for the leviathan of Birr Castle; but in a climate like that of Ireland the occasions must be rare when even that limit can be reached. Indeed, the experience acquired by its use plainly shows that atmospheric rather than mechanical difficulties impede a still further increase of telescopic power. Its construction may accordingly be said to mark the *ne plus ultra* of effort in one direction, and the beginning of its conversion towards another. It became thenceforward more and more obvious that the conditions of observation must be ameliorated before any added efficacy could be given to it. The full effect of an uncertain climate in nullifying optical improvements was recognised, and the attention of astronomers began to be turned towards the advantages offered by more tranquil and more translucent skies.

Scarcely less important for the practical uses of astronomy than the optical qualities of the telescope is the manner of its mounting. The most admirable performance of the optician can render but unsatisfactory service if its mechanical accessories are ill-arranged or inconvenient. Thus the astronomer is ultimately dependent upon the mechanician; and so excellently have his needs been served, that the history of the ingenious contrivances by which discoveries have been prepared would supply a subject (here barely glanced at) not far inferior in extent and instruction to the history of those discoveries themselves.

There are two chief modes of using the telescope, to which all others may be considered subordinate.[335] Either it may be invariably directed towards the south, with no motion save in the plane of the meridian, so as to intercept the heavenly bodies at the moment of transit across that plain; or it may be arranged so as to follow the daily revolution of the sky, thus keeping the object viewed permanently in sight instead of simply noting the instant of its flitting across the telescopic field. The first plan is that of the "transit instrument," the second that of the "equatoreal." Both were, by a remarkable coincidence, introduced about 1690[336] by Olaus Römer, the brilliant Danish astronomer who first measured the velocity of light.

The uses of each are entirely different. With the transit, the really fundamental task of astronomy—the determination of the movements of the heavenly bodies—is mainly accomplished; while the investigation of their nature and peculiarities is best conducted with the equatoreal. One is the instrument of mathematical, the other of descriptive astronomy. One furnishes the materials with which theories are constructed and the tests by which they are corrected; the other registers new facts, takes note of new appearances, sounds the depths and peers into every nook of the heavens.

The great improvement of giving to a telescope equatoreally mounted an automatic movement by connecting it with clockwork, was proposed in 1674 by Robert Hooke. Bradley in 1721 actually observed Mars with a telescope "moved by a machine that made it keep pace with the stars;"[337] and Von Zach relates[338] that he had once followed Sirius for twelve hours with a "heliostat" of Ramsden's construction. But these eighteenth-century attempts were of no practical effect. Movement by clockwork was virtually a complete novelty when it was adopted by Fraunhofer in 1824 to the Dorpat refractor. By simply giving to an axis unvaryingly directed towards the celestial pole an equable rotation with a period of twenty-four hours, a telescope attached to it, and pointed in *any* direction, will trace out on the sky a parallel of declination, thus necessarily accompanying the movement of any star upon which it may be fixed. It accordingly forms part of the large sum of Fraunhofer's merits to have secured this inestimable advantage to observers.

Sir John Herschel considered that Lassell's application of equatoreal mounting to a nine-inch Newtonian in 1840 made an epoch in the history of "that eminently British instrument, the reflecting telescope."[339] Nearly a century earlier,[340] it is true, Short had fitted one of his Gregorians to a complicated system of circles in such a manner that, by moving a handle, it could be made to follow the revolution of the sky; but the arrangement did not obtain, nor did it deserve, general adoption. Lassell's plan was a totally different one; he employed the crossed axes of the true equatoreal, and his success removed, to a great extent, the fatal objection of inconvenience in use, until then unanswerably urged against reflectors. The very largest of these can now be mounted equatoreally; even the Rosse, within its limited range, has been for some years provided with a movement by clockwork along declination-parallels.

The art of accurately dividing circular arcs into the minute equal parts which serve as the units of astronomical measurement, remained, during the whole of the eighteenth century, almost exclusively in English hands. It was brought to a high degree of perfection by Graham, Bird and Ramsden, all of whom, however, gave the preference to the old-fashioned mural quadrant and zenith-sector over the entire circle, which Römer had already found the advantage of employing. The five-foot vertical circle, which Piazzi with some difficulty induced Ramsden to complete for him in 1789, was the first divided instrument constructed in what may be called the modern style. It was provided with magnifiers for reading off the divisions (one of the neglected improvements of Römer), and was set up above a smaller horizontal circle, forming an "altitude and azimuth" combination (again Römer's invention), by which both the elevation of a celestial object above the horizon and its position as referred to the horizon could be measured. In the same year, Borda invented the "repeating circle" (the principle of which had been suggested by Tobias Mayer in 1756[341]), a device for exterminating, so far as possible, errors of graduation by *repeating* an observation with different parts of the limb. This was perhaps the earliest systematic effort to correct the imperfections of instruments by the manner of their use.

The manufacture of astronomical circles was brought to a very refined state of excellence early in the nineteenth century by Reichenbach at Munich, and after 1818 by Repsold at Hamburg. Bessel states[342] that the "reading-off" on an instrument of the kind by the latter artist was accurate to about 1/80th of a human hair. Meanwhile the traditional reputation of the English school was fully sustained; and Sir George Airy did not hesitate to express his opinion that the new method of graduating circles, published by Troughton in 1809,[343] was the "greatest improvement ever made in the art of instrument-making."[344] But a more secure road to improvement than that of mere mechanical exactness was pointed out by Bessel. His introduction of a regular theory of instrumental errors might almost be said to have created a new art of observation. Every instrument, he declared in memorable words,[345] must be twice made—once by the artist, and again by the observer. Knowledge is power. Defects that are ascertained and can be allowed for are as good as non-existent. Thus the truism that the best instrument is worthless in the hands of a careless or clumsy observer, became supplemented by the converse maxim, that defective appliances may, through skilful use, be made to yield valuable results. The Königsberg observations—of which the first instalment was published in 1815—set the example of regular "reduction" for instrumental errors. Since then, it has become an elementary part of an astronomer's duty to study the *idiosyncrasy* of each one of the mechanical contrivances at his disposal, in order that its inevitable, but now certified deviations from ideal accuracy may be included amongst the numerous corrections by which the pure essence of even approximate truth is distilled from the rude impressions of sense.

Nor is this enough; for the casual circumstances attending each observation have to be taken into account with no less care than the inherent or *constitutional* peculiarities of the instrument with which it is made. There is no “once for all” in astronomy. Vigilance can never sleep; patience can never tire. Variable as well as constant sources of error must be anxiously heeded; one infinitesimal inaccuracy must be weighed against another; all the forces and vicissitudes of nature—frosts, dews, winds, the interchanges of heat, the disturbing effects of gravity, the shiverings of the air, the tremors of the earth, the weight and vital warmth of the observer’s own body, nay, the rate at which his brain receives and transmits its impressions, must all enter into his calculations, and be sifted out from his results.

It was in 1823 that Bessel drew attention to discrepancies in the times of transits given by different astronomers.[346] The quantities involved were far from insignificant. He was himself nearly a second in advance of all his contemporaries, Argelander lagging behind him as much as a second and a quarter. Each individual, in fact, was found to have a certain definite *rate of perception*, which, under the name of “personal equation,” now forms so important an element in the correction of observations that a special instrument for accurately determining its amount in each case is in actual use at Greenwich.

Such are the refinements upon which modern astronomy depends for its progress. It is a science of hairbreadths and fractions of a second. It exists only by the rigid enforcement of arduous accuracy and unwearying diligence. Whatever secrets the universe still has in store for man will only be communicated on these terms. They are, it must be acknowledged, difficult to comply with. They involve an unceasing struggle against the infirmities of his nature and the instabilities of his position. But the end is not unworthy the sacrifices demanded. One additional ray of light thrown on the marvels of creation—a single, minutest encroachment upon the strongholds of ignorance—is recompense enough for a lifetime of toil. Or rather, the toil is its own reward, if pursued in the lofty spirit which alone becomes it. For it leads through the abysses of space and the unending vistas of time to the very threshold of that infinity and eternity of which the disclosure is reserved for a life to come.

FOOTNOTES:

[305] Grant, *Hist. Astr.*, p. 527.

[306] *Optica Promota*, p. 93.

[307] *Phil. Trans.*, vol. xxxii., p. 383.

[308] *Ibid.*, vol. xc., p. 65.

[309] Cassegrain, a Frenchman, substituted in 1672 a *convex* for a *concave* secondary speculum. The tube was thereby enabled to be shortened by twice the focal length of the mirror in question.

The great Melbourne reflector (four feet aperture, by Grubb) is constructed upon this plan.

[310] *Phil. Trans.*, vol. civ., p. 275, *note*.

[311] *Phil. Trans.*, vol. xc., p. 70. With the forty-foot, however, only very moderate powers seemed to have been employed, whence Dr. Robinson argued a deficiency of defining power. *Proc. Roy. Irish Ac.*, vol. ii., p. 11.

[312] *Phil. Trans.*, vol. lxxi., p. 492.

[313] It is remarkable that, as early as 1695, the possibility of an achromatic combination was inferred by David Gregory from the structure of the human eye. See his *Catoptricæ et Dioptricæ Sphericæ Elementa*, p. 98.

[314] Wolf, *Biographien*, Bd. ii., p. 301.

[315] *Month. Not.*, vol. i., p. 153. *note*.

[316] Henrivaux, *Encyclopédie Chimique*, t. v., fasc. 5, p. 363.

[317] See *ante*, p. 83.

[318] *Phil. Trans.*, vol. vii., p. 4007.

[319] J. Herschel, *The Telescope*, p. 39.

[320] *Month. Not.*, vol. xxix., p. 125.

[321] A slight excess of copper renders the metal easier to work, but liable to tarnish. Robinson, *Proc. Roy. Irish Ac.*, vol. ii., p. 4.

[322] *Brit. Ass.*, 1843, Dr. Robinson's closing Address. *Athenæum*, Sept. 23, p. 866.

[323] *The Telescope*, p. 82.

[324] Lord Rosse in *Phil. Trans.*, vol. cxl., p. 302.

[325] This method is the same in principle with that applied by Grubb in 1834 to a 15-inch speculum for the observatory of Armagh. *Phil. Trans.*, vol. clix., p. 145.

[326] Robinson, *Proc. Roy. Ir. Ac.*, vol. iii., p. 120.

[327] *Astr. Nach.*, No. 536.

[328] Airy, *Month. Not.*, vol. ix., p. 120.

[329] *Astronomical Journal* (Gould's), vol. ii., p. 97.

[330] *Ibid.*, p. 160.

[331] Lord Rosse in *Phil. Trans.*, vol. cxl., p. 505.

[332] No. 2343 of Herschel's (1864) Catalogue. Before 1850 a star was visible in each of the two larger openings by which it is pierced; since then, one only. Webb, *Celestial Objects* (4th ed.), p. 409.

[333] *Mem. Am. Ac.*, vol. iii., p. 87; *Astr. Nach.*, No. 611.

[334] *Pop. Astr.*, p. 145.

[335] This statement must be taken in the most general sense. Supplementary observations of great value are now made at Greenwich with the altitude and azimuth instrument, which likewise served Piazzi to determine the places of his stars; while a "prime vertical instrument" is prominent at Pulkowa.

[336] As early as 1620, according to R. Wolf (*Ges. der Astr.*, p. 587), Father Scheiner made the experiment of connecting a telescope with an axis directed to the pole, while Chinese "equatoreal armillæ," dating from the thirteenth century, existed at Pekin until 1900, when they were carried off as "loot" to Berlin. J. L. E. Dreyer, *Copernicus*, vol. i., p. 134.

[337] *Miscellaneous Works*, p. 350.

[338] *Astr. Jahrbuch*, 1799 (published 1796), p. 115.

[339] *Month. Not.*, vol. xli., p. 189.

[340] *Phil. Trans.*, vol. xlvi., p. 242.

[341] Grant, *Hist. of Astr.*, p. 487.

[342] *Pop. Vorl.*, p. 546.

[343] *Phil. Trans.*, vol. xcix., p. 105.

[344] *Report Brit. Ass.*, 1832, p. 132.

[345] *Pop. Vorl.*, p. 432.

[346] C. T. Anger, *Grundzüge der neucren astronomischen Beobachtungs-Kunst*, p. 3.

PART II

RECENT PROGRESS OF ASTRONOMY

CHAPTER I

FOUNDATION OF ASTRONOMICAL PHYSICS

In the year 1826, Heinrich Schwabe of Dessau, elated with the hope of speedily delivering himself from the hereditary incubus of an apothecary's shop,[347] obtained from Munich a small telescope and began to observe the sun. His choice of an object for his researches was instigated by his friend Harding of Göttingen. It was a peculiarly happy one. The changes visible in the solar surface were then generally regarded as no less capricious than the changes in the skies of our temperate regions. Consequently, the reckoning and registering of sun-spots was a task hardly more inviting to an astronomer than the reckoning and registering of summer clouds. Cassini, Keill, Lemonnier, Lalande, were unanimous in declaring that no trace of regularity could be detected in their appearances or effacements.[348] Delambre pronounced them "more curious than really useful."[349] Even Herschel, profoundly as he studied them, and intimately as he was convinced of their importance as symptoms of solar activity, saw no reason to suspect that their abundance and scarcity were subject to orderly alternation. One man alone in the eighteenth century, Christian Horrebow of Copenhagen, divined their periodical character, and foresaw the time when the effects of the sun's vicissitudes upon the globes revolving round him might be investigated with success; but this prophetic utterance was of the nature of a soliloquy rather than of a communication, and remained hidden away in an unpublished journal until 1859, when it was brought to light in a general ransacking of archives.[350]

Indeed, Schwabe himself was far from anticipating the discovery which fell to his share. He compared his fortune to that of Saul, who, seeking his father's asses, found a kingdom.[351] For the hope which inspired his early resolution lay in quite another direction. His patient ambush was laid for a possible intramercurial planet, which, he thought, must sooner or later betray its existence in crossing the face of the sun. He took, however, the most effectual measures to secure whatever new knowledge might be accessible. During forty-three years his "imperturbable telescope"[352] never failed, weather and health permitting, to bring in its daily report as to how many, or if any, spots were visible on the sun's disc, the information obtained being day by day recorded on a simple and unvarying system. In 1843 he made his first announcement of a probable decennial period,[353] but it met with no general attention; although Julius Schmidt of Bonn (afterwards director of the Athens Observatory) and Gautier of Geneva were impressed with his figures, and Littrow had himself, in 1836,[354] hinted at the likelihood of some kind of regular recurrence. Schwabe, however, worked on, gathering each year fresh evidence of a law such as he had indicated; and when Humboldt published in 1851, in the third volume of his *Kosmos*,[355] a table of the sun-spot statistics collected by him from 1826 downwards, the strength of his case was perceived with, so to speak, a start of surprise; the reality and importance of the discovery were simultaneously recognised, and the persevering Hofrath of Dessau found himself famous among astronomers. His merit—recognised by the bestowal of the Astronomical Society's Gold Medal in 1857—consisted in his choice of an original and appropriate line of work, and in the admirable tenacity of purpose with which he pursued it. His resources and acquirements were those of an ordinary amateur; he was distinguished solely by the unfortunately rare power of turning both to the best account. He died where he was born and had lived, April 11, 1875, at the ripe age of eighty-six.

Meanwhile an investigation of a totally different character, and conducted by totally different means, had been prosecuted to a very similar conclusion. Two years after Schwabe began his solitary observations, Humboldt gave the first impulse, at the Scientific Congress of Berlin in 1828, to a great international movement for attacking simultaneously, in various parts of the globe, the complex problem of terrestrial magnetism. Through the genius and energy of Gauss, Göttingen became its centre. Thence new apparatus, and a new system for its employment, issued; there, in 1833, the first regular magnetic observatory was founded, whilst at Göttingen was fixed the universal time-standard for magnetic observations. A letter addressed by Humboldt in April, 1836, to the Duke of Sussex as President of the Royal Society, enlisted the co-operation of England. A network of magnetic stations was spread all over the British dominions, from Canada to Van Diemen's Land; measures were concerted with foreign authorities, and an expedition was fitted out, under the able command of Captain (afterwards Sir James) Clark Ross, for the special purpose of bringing intelligence on the subject from the dismal neighbourhood of the South Pole. In 1841, the elaborate organisation created by the disinterested efforts of scientific "agitators" was complete; Gauss's "magnetometers" were vibrating under the view of attentive observers in five continents, and simultaneous results began to be recorded.

Ten years later, in September, 1851, Dr. John Lamont, the Scotch director of the Munich Observatory, in reviewing the magnetic observations made at Göttingen and Munich from 1835 to 1850, perceived with some surprise that they gave unmistakable indications of a period which he estimated at 10-1/3 years.[356] The manner in which this periodicity manifested itself requires a word of explanation. The observations in question referred to what is called the "declination" of the magnetic needle—that is, to the position assumed by it with reference to the points of the compass when moving freely in a horizontal plane. Now this position—as was discovered by Graham in 1722—is subject to a small daily fluctuation, attaining its maximum towards the east about 8 A.M., and its maximum towards the west shortly before 2 P.M. In other words, the direction of the needle approaches (in these countries at the present time) nearest to the true north some four hours before noon, and departs farthest from it between one and two hours after noon. It was the *range* of this daily variation that Lamont found to increase and diminish once in every 10-1/3 years.

In the following winter, Sir Edward Sabine, ignorant as yet of Lamont's conclusion, undertook to examine a totally different set of observations. The materials in his hands had been collected at the British colonial stations of Toronto and Hobarton from 1843 to 1848, and had reference, not to the regular diurnal swing of the needle, but to those curious spasmodic vibrations, the inquiry into the laws of which was the primary object of the vast organisation set on foot by Humboldt and Gauss. Yet the upshot was practically the same. Once in about ten years, magnetic disturbances (termed by Humboldt "storms") were perceived to reach a maximum of violence and frequency. Sabine was the first to note the coincidence between this unlooked-for result and Schwabe's sun-spot period. He showed that, so far as observation had yet gone, the two cycles of change agreed perfectly both in duration and phase, maximum corresponding to maximum, minimum to minimum. What the nature of the connection could be that bound together by a common law effects so dissimilar as the rents in the luminous garment of the sun, and the swayings to and fro of the magnetic needle, was and still remains beyond the reach of well-founded theory; but the fact was from the first undeniable.

The memoir containing this remarkable disclosure was presented to the Royal Society, March 18, and read May 6, 1852.[357] On the 31st of July following, Rudolf Wolf at Berne,[358] and on the 18th of August, Alfred Gautier at Sion,[359] announced, separately and independently, perfectly similar conclusions. This triple event is perhaps the most striking instance of the successful employment of the Baconian method of co-operation in discovery, by which "particulars" are amassed by one set of investigators—corresponding to the "Depredators" and "Inoculators" of Solomon's House—while inductions are drawn from them by another and a higher class—the "Interpreters of Nature." Yet even here the convergence of two distinct lines of research was wholly fortuitous, and skilful combination owed the most brilliant part of its success to the unsought bounty of what we call Fortune.

The exactness of the coincidence thus brought to light was fully confirmed by further inquiries. A diligent search through the scattered records of sun-spot observations, from the time of Galileo and Scheiner onwards, put Wolf[360] in possession of materials by which he was enabled to correct Schwabe's loosely-indicated decennial period to one of slightly over eleven (11.11) years; and he further showed that this fell in with the ebb and flow of magnetic change even better than Lamont's 10-1/3 year cycle. The analogy was also pointed out between the "light-curve," or zig-zagged line representing on paper the varying intensity in the lustre of certain stars, and the similar delineation of spot-frequency; the ascent from minimum to maximum being, in both cases, usually steeper than the descent from maximum to minimum; while an additional point of resemblance was furnished by the irregularities in height of the various maxima. In other words, both the number of spots on the sun and the brightness of variable stars increase, as a rule, more rapidly than they decrease; nor does the amount of that increase, in either instance, show any approach to uniformity.

The endeavour, suggested by the very nature of the phenomenon, to connect sun-spots with weather was less successful. The first attempt of the kind was made by Sir William Herschel in 1801, and a very notable one it was. Meteorological statistics, save of the scantiest and most casual kind, did not then exist; but the price of corn from year to year was on record, and this, with full recognition of its inadequacy, he adopted as his criterion. Nor was he much better off for information respecting the solar condition. What little he could obtain, however, served, as he believed, to confirm his surmise that a copious emission of light and heat accompanies an abundant formation of "openings" in the dazzling substance whence our supply of those indispensable commodities is derived.[361] He gathered, in short, from his inquiries very much what he had expected to gather, namely, that the price of wheat was high when the sun showed an unsullied surface, and that food and spots became plentiful together.[362]

Yet this plausible inference was scarcely borne out by a more exact collocation of facts. Schwabe failed to detect any reflection of the sun-spot period in his meteorological register. Gautier[363] reached a provisional conclusion the reverse—though not markedly the reverse—of Herschel's. Wolf, in 1852, derived from an examination of Vogel's collection of Zürich Chronicles (1000-1800 A.D.) evidence showing (as he thought) that minimum years were usually wet and stormy, maximum years dry and genial;[364] but a subsequent review of the subject in 1859 convinced him that no relation of any kind between the two kinds of effects was traceable.[365] With the singular affection of our atmosphere known as the Aurora Borealis (more properly Aurora Polaris) the case was different. Here the Zürich Chronicles set Wolf on the right track in leading him to associate such luminous manifestations with a disturbed condition of the sun; since subsequent detailed observation has exhibited the curve of auroral frequency as following with such fidelity the jagged lines figuring to the eye the fluctuations of solar and magnetic activity, as to leave no reasonable doubt that all three rise and sink together under the influence of a common cause. As long ago as 1716,[366] Halley had conjectured that the Northern Lights were due to magnetic "effluvia," but there was no evidence on the subject forthcoming until Hiorter observed at Upsala in 1741 their agitating influence upon the magnetic needle. That the effect was no casual one was made superabundantly clear by Arago's researches in 1819 and subsequent years. Now both were perceived to be swayed by the same obscure power of cosmical disturbance.

The sun is not the only one of the heavenly bodies by which the magnetism of the earth is affected. Proofs of a similar kind of lunar action were laid by Kreil in 1841 before the Bohemian Society of Sciences, and with minor corrections were fully substantiated by Sabine's more extended researches. It was thus ascertained that each lunar day, or the interval of twenty-four hours and about fifty-four minutes between two successive meridian passages of our satellite, is marked by a perceptible, though very small, double oscillation of the needle—two progressive movements from east to west, and two returns from west to east.[367] Moreover, the lunar, like the solar influence (as was proved in each case by Sabine's analysis of the Hobarton and Toronto observations), extends to all three "magnetic elements," affecting not only the position of the horizontal or *declination* needle, but also the dip and intensity. It seems not unreasonable to attribute some portion of the same subtle power to the planets and even to the stars, though with effects rendered imperceptible by distance.

We have now to speak of the discovery and application to the heavenly bodies of a totally new method of investigation. Spectrum analysis may be shortly described as a mode of distinguishing the various species of matter by the kind of light proceeding from each. This definition at once explains how it is that, unlike every other system of chemical analysis, it has proved available in astronomy. Light, so far as *quality* is concerned, ignores distance. No intrinsic change, that we yet know of, is produced in it by a journey from the farthest bounds of the visible universe; so that, provided only that in *quantity* it remain sufficient for the purpose, its peculiarities can be equally well studied whether the source of its vibrations be one foot or a hundred billion miles distant. Now the most obvious distinction between one kind of light and another resides in colour. But of this distinction the eye takes cognisance in an æsthetic, not in a scientific sense. It finds gladness in the "thousand tints" of nature, but can neither analyse nor define them. Here the refracting prism—or the combination of prisms known as the "spectroscope"—comes to its aid, teaching it to measure as well as to perceive. It furnishes, in a word, an accurate scale of colour. The various rays which, entering the eye together in a confused crowd, produce a compound impression made up of undistinguishable elements, are, by the mere passage through a triangular piece of glass, separated one from the other, and ranged side by side in orderly succession, so that it becomes possible to tell at a glance what kinds of light are present, and what absent. Thus, if we could only be assured that the various chemical substances when made to glow by heat, emit characteristic rays—rays, that is, occupying a place in the spectrum reserved for them, and for them *only*—we should at once be in possession of a mode of identifying such substances with the utmost readiness and certainty. This assurance, which forms the solid basis of spectrum analysis, was obtained slowly and with difficulty.

The first to employ the prism in the examination of various flames (for it is only in a state of vapour that matter emits distinctive light) was a young Scotchman named Thomas Melvill, who died in 1753, at the age of twenty-seven. He studied the spectrum of burning spirits, into which were successively introduced sal ammoniac, potash, alum, nitre, and sea-salt, and observed the singular predominance, under almost all circumstances, of a particular shade of yellow light, perfectly definite in its degree of refrangibility[368]—in other words, taking up a perfectly definite position in the spectrum. His experiments were repeated by Morgan,[369] Wollaston, and—with far superior precision and diligence—by Fraunhofer.[370] The great Munich optician, whose work was completely original, rediscovered Melvill's deep yellow ray and measured its place in the colour-scale. It has since become well known as the "sodium line," and has played a very important part in the history of spectrum analysis. Nevertheless, its ubiquity and conspicuousness long impeded progress. It was elicited by the combustion of a surprising variety of substances—sulphur, alcohol, ivory, wood, paper; its persistent visibility suggesting the accomplishment of some universal process of nature rather than the presence of one individual kind of matter. But if spectrum analysis were to exist as a science at all, it could only be by attaining certainty as to the unvarying association of one special substance with each special quality of light.

Thus perplexed, Fox Talbot[371] hesitated in 1826 to enounce this fundamental principle. He was inclined to believe that the presence in the spectrum of any individual ray told unerringly of the volatilisation in the flame under scrutiny of some body as whose badge or distinctive symbol that ray might be regarded; but the continual prominence of the yellow beam staggered him. It appeared, indeed, without fail where sodium *was*; but it also appeared where it might be thought only reasonable to conclude that sodium *was not*. Nor was it until thirty years later that William Swan,[372] by pointing out the extreme delicacy of the spectral test, and the singularly wide dispersion of sodium, made it appear probable (but even then only probable) that the questionable yellow line was really due invariably to that substance. Common salt (chloride of sodium) is, in fact, the most diffusive of solids. It floats in the air; it flows with water; every grain of dust has its attendant particle; its absolute exclusion approaches the impossible. And withal, the light that it gives in burning is so intense and concentrated, that if a single grain be divided into 180 million parts, and one alone of such inconceivably minute fragments be present in a source of light, the spectroscope will show unmistakably its characteristic beam.

Amongst the pioneers of knowledge in this direction were Sir John Herschel[373]—who, however, applied himself to the subject in the interests of optics, not of chemistry—W. A. Miller,[374] and Wheatstone. The last especially made a notable advance when, in the course of his studies on the "prismatic decomposition" of the electric light, he reached the significant conclusion that the rays visible in its spectrum were different for each kind of metal employed as "electrodes."[375] Thus indications of a wider principle were to be found in several quarters, but no positive certainty on any single point was obtained, until, in 1859, Gustav Kirchhoff, professor of physics in the University of Heidelberg, and his colleague, the eminent chemist Robert Bunsen, took the matter in hand. By them the general question as to the necessary and invariable connection of certain rays in the spectrum with certain kinds of matter, was first resolutely confronted, and first definitely answered. It was answered affirmatively—else there could have been no science of spectrum analysis—as the result of experiments more numerous, more stringent, and more precise than had previously been undertaken.[376] And the assurance of their conclusion was rendered doubly sure by the discovery, through the peculiarities of their light alone, of two new metals, named from the blue and red rays by which they were respectively distinguished, "cæsium," and "rubidium."[377] Both were immediately afterwards actually obtained in small quantities by evaporation of the Durckheim mineral waters.

The link connecting this important result with astronomy may now be indicated. In the year 1802 it occurred to William Hyde Wollaston to substitute for the round hole used by Newton and his successors for the admittance of light to be examined with the prism, an elongated "crevice" 1/20th of an inch in width. He thereupon perceived that the spectrum, thus formed of light, as it were, *purified* by the abolition of overlapping images, was traversed by seven dark lines. These he took to be natural boundaries of the various colours,[378] and satisfied with this quasi-explanation, allowed the subject to drop. It was independently taken up after twelve years by a man of higher genius. In the course of experiments on light, directed towards the perfecting of his achromatic lenses, Fraunhofer, by means of a slit and a telescope, made the surprising discovery that the solar spectrum is crossed, not by seven, but by thousands of obscure transverse streaks.[379] Of these he counted some 600, and carefully mapped 324, while a few of the most conspicuous he set up (if we may be permitted the expression) as landmarks, measuring their distances apart with a theodolite, and affixing to them the letters of the alphabet, by which they are still universally known. Nor did he stop here. The same system of examination applied to the rest of the heavenly bodies showed the mild effulgence of the moon and planets to be deficient in precisely the same rays as sunlight; while in the stars it disclosed the differences in likeness which are always an earnest of increased knowledge. The spectra of Sirius and Castor, instead of being delicately ruled crosswise throughout, like that of the sun, were seen to be interrupted by three massive bars of darkness—two in the blue and one in the green;[380] the light of Pollux, on the other hand, seemed precisely similar to sunlight attenuated by distance or reflection, and that of Capella, Betelgeux, and Procyon to share some of its peculiarities. One solar line especially—that marked in his map with the letter D—proved common to all the four last-mentioned stars; and it was remarkable that it exactly coincided in position with the conspicuous yellow beam (afterwards, as we have said, identified with the light of glowing sodium) which he had already found to accompany most kinds of combustion. Moreover, both the *dark* solar and the *bright* terrestrial "D lines" were displayed by the refined Munich appliances as double.

In this striking correspondence, discovered by Fraunhofer in 1815, was contained the very essence of solar chemistry; but its true significance did not become apparent until long afterwards. Fraunhofer was by profession, not a physicist, but a practical optician. Time pressed; he could not and would not deviate from his appointed track; all that was possible to him was to indicate the road to discovery, and exhort others to follow it.[381]

Partially and inconclusively at first this was done. The "fixed lines" (as they were called) of the solar spectrum took up the position of a standing problem, to the solution of which no approach seemed possible. Conjectures as to their origin were indeed rife. An explanation put forward by Zantedeschi[382] and others, and dubiously favoured by Sir David Brewster and Dr. J. H. Gladstone,[383] was that they resulted from "interference"—that is, a destruction of the motion producing in our eyes the sensation of light, by the superposition of two light-waves in such a manner that the crests of one exactly fill up the hollows of the other. This effect was supposed to be brought about by imperfections in the optical apparatus employed.

A more plausible view was that the atmosphere of the earth was the agent by which sunlight was deprived of its missing beams. For a few of them this is actually the case. Brewster found in 1832 that certain dark lines, which were invisible when the sun stood high in the heavens, became increasingly conspicuous as he approached the horizon.[384] These are the well-known "atmospheric lines;" but the immense majority of their companions in the spectrum remain quite unaffected by the thickness of the stratum of air traversed by the sunlight containing them. They are then obviously due to another cause.

There remained the true interpretation—absorption in the *sun's* atmosphere; and this, too, was extensively canvassed. But a remarkable observation made by Professor Forbes of Edinburgh[385] on the occasion of the annular eclipse of May 15, 1836, appeared to throw discredit upon it. If the problematical dark lines were really occasioned by the stoppage of certain rays through the action of a vaporous envelope surrounding the sun, they ought, it seemed, to be strongest in light proceeding from his edges, which, cutting that envelope obliquely, passed through a much greater depth of it. But the circle of light left by the interposing moon, and of course derived entirely from the rim of the solar disc, yielded to Forbes's examination precisely the same spectrum as light coming from its central parts. This circumstance helped to baffle inquirers, already sufficiently perplexed. It still remains an anomaly, of which no satisfactory explanation has been offered.

Convincing evidence as to the true nature of the solar lines was however at length, in the autumn of 1859, brought forward at Heidelburg. Kirchhoff's *experimentum crucis* in the matter was a very simple one. He threw bright sunshine across a space occupied by vapour of sodium, and perceived with astonishment that the dark Fraunhofer line D, instead of being effaced by flame giving a luminous ray of the same refrangibility, was deepened and thickened by the superposition.

He tried the same experiment, substituting for sunbeams light from a Drummond lamp, and with similar result. A dark furrow, corresponding in every respect to the solar D-line, was instantly seen to interrupt the otherwise unbroken radiance of its spectrum. The inference was irresistible, that the effect thus produced artificially was brought about naturally in the same way, and that sodium formed an ingredient in the glowing atmosphere of the sun.[386] This first discovery was quickly followed up by the identification of numerous bright rays in the spectra of other metallic bodies with others of the hitherto mysterious Fraunhofer lines. Kirchhoff was thus led to the conclusion that (besides sodium) iron, magnesium, calcium, and chromium, are certainly solar constituents, and that copper, zinc, barium, and nickel are also present, though in smaller quantities.[387] As to cobalt, he hesitated to pronounce, but its existence in the sun has since been established.

These memorable results were founded upon a general principle first enunciated by

Kirchhoff in a communication to the Berlin Academy, December 15, 1859, and afterwards more fully developed by him.[388] It may be expressed as follows: Substances of every kind are opaque to the precise rays which they emit at the same temperature; that is to say, they stop the kinds of light or heat which they are then actually in a condition to radiate. But it does not follow that *cool* bodies absorb the rays which they would give out if sufficiently heated. Hydrogen at ordinary temperatures, for instance, is almost perfectly transparent, but if raised to the glowing point—as by the passage of electricity—it *then* becomes capable of arresting, and at the same time of displaying in its own spectrum light of four distinct colours.

This principle is fundamental to solar chemistry. It gives the key to the hieroglyphics of the Fraunhofer lines. The identical characters which are written *bright* in terrestrial spectra are written *dark* in the unrolled sheaf of sun-rays; the meaning remains unchanged. It must, however, be remembered that they are only *relatively* dark. The substances stopping those particular tints in the neighbourhood of the sun are at the same time vividly glowing with the very same. Remove the dazzling solar background, by contrast with which they show as obscure, and they will be seen, and, at critical moments, actually have been seen, in all their native splendour. It is because the atmosphere of the sun is cooler than the globe it envelops that the different kinds of vapour constituting that atmosphere take more than they give, absorb more light than they are capable of emitting; raise them to the same temperature as the sun itself, and their powers of emission and absorption being brought exactly to the same level, the thousands of dusky rays in the solar spectrum will be at once obliterated.

The establishment of the terrestrial science of spectrum analysis was due, as we have seen, equally to Kirchhoff and Bunsen, but its celestial application to Kirchhoff alone. He effected this object of the aspirations, more or less dim, of many other thinkers and workers, by the union of two separate, though closely related lines of research—the study of the different kinds of light *emitted* by various bodies, and the study of the different kinds of light *absorbed* by them. The latter branch appears to have been first entered upon by Dr. Thomas Young in 1803;[389] it was pursued by the younger Herschel,[390] by William Allen Miller, Brewster, and Gladstone. Brewster indeed made, in 1833,[391] a formal attempt to found what might be called an inverse system of analysis with the prism based upon absorption; and his efforts were repeated, just a quarter of a century later, by Gladstone.[392] But no general point of view was attained; nor, it may be added, was it by this path attainable.

Kirchhoff's map of the solar spectrum, drawn to scale with exquisite accuracy, and printed in three shades of ink to convey the graduated obscurity of the lines, was published in the Transactions of the Berlin Academy for 1861 and 1862.[393] Representations of the principal lines belonging to various elementary bodies formed, as it were, a series of marginal notes accompanying the great solar scroll, enabling the veriest tiro in the new science to decipher its meaning at a glance. Where the dark solar and bright metallic rays agreed in position, it might safely be inferred that the metal emitting them was a solar constituent; and such coincidences were numerous. In the case of iron alone, no less than sixty occurred in one-half of the spectral area, rendering the chances[394] absolutely overwhelming against mere casual conjunction. The preparation of this elaborate picture proved so trying to the eyes that Kirchhoff was compelled by failing vision to resign the latter half of the task to his pupil Hofmann. The complete map measured nearly eight feet in length.

The conclusions reached by Kirchhoff were no sooner announced than they took their place, with scarcely a dissenting voice, among the established truths of science. The broad result, that the dark lines in the spectrum of the sun afford an index to its chemical composition no less reliable than any of the tests used in the laboratory, was equally captivating to the imagination of the vulgar, and authentic in the judgment of the learned; and, like all genuine advances in the knowledge of Nature, it stimulated curiosity far more than it gratified it. Now the history of how discoveries were missed is often quite as instructive as the history of how they were made; it may then be worth while to expend a few words on the thoughts and trials by which, in the present case, the actual event was heralded.

Three times it seemed on the verge of being anticipated. The experiment, which in Kirchhoff's hands proved decisive, of passing sunlight through glowing vapours and examining the superposed spectra, was performed by Professor W. A. Miller of King's College in 1845.[395] Nay, more, it was performed with express reference to the question, then already (as has been noted) in debate, of the possible production of Fraunhofer's lines by absorption in a solar atmosphere. Yet it led to nothing.

Again, at Paris in 1849, with a view to testing the asserted coincidence between the solar D-line and the bright yellow beam in the spectrum of the electric arc (really due to the unsuspected presence of sodium), Léon Foucault threw a ray of sunshine across the arc and observed its spectrum.[396] He was surprised to see that the D-line was rendered more intensely dark by the combination of lights. To assure himself still further, he substituted a reflected image of one of the white-hot carbon-points for the sunbeam, with an identical result. *The same ray was missing.* It needed but another step to have generalised this result, and thus laid hold of a natural truth of the highest importance; but that step was not taken. Foucault, keen and brilliant though he was, rested satisfied with the information that the *voltaic arc* had the power of stopping the kind of light emitted by it; he asked no further question, and was consequently the bearer of no further intelligence on the subject.

The truth conveyed by this remarkable experiment was, however, divined by one eminent man. Professor Stokes of Cambridge stated to Sir William Thomson (now Lord Kelvin), shortly after it had been made, his conviction that an absorbing atmosphere of sodium surrounded the sun. And so forcibly was his hearer impressed with the weight of the argument based upon the absolute agreement of the D-line in the solar spectrum with the yellow ray of burning sodium (then freshly certified by W. H. Miller), combined with Foucault's "reversal" of that ray, that he regularly inculcated, in his public lectures on natural philosophy at Glasgow, five or six years before Kirchhoff's discovery, not only the *fact* of the presence of sodium in the solar neighbourhood, but also the *principle* of the study of solar and stellar chemistry in the spectra of flames.[397] Yet it does not appear to have occurred to either of these two distinguished professors—themselves among the foremost of their time in the successful search for new truths—to verify practically a sagacious conjecture in which was contained the possibility of a scientific revolution. It is just to add, that Kirchhoff was unacquainted, when he undertook his investigation, either with the experiment of Foucault or the speculation of Stokes.

For C. J. Ångström, on the other hand, perhaps somewhat too much has been claimed in the way of anticipation. His *Optical Researches* appeared at Upsala in 1853, and in their English garb two years later.[398] They were undoubtedly pregnant with suggestion, yet made no epoch in discovery. The old perplexities continued to prevail after, as before their publication. To Ångström, indeed, belongs the great merit of having revived Euler's principle of the equivalence of emission and absorption; but he revived it in its original crude form, and without the qualifying proviso which alone gave it value as a clue to new truths. According to his statement, a body absorbs all the series of vibrations it is, under any circumstances, capable of emitting, as well as those connected with them by simple harmonic relations. This is far too wide. To render it either true or useful, it had to be reduced to the cautious terms employed by Kirchhoff. Radiation strictly and necessarily corresponds with absorption only *when the temperature is the same*. In point of fact, Ångström was still, in 1853, divided between adsorption and interference as the mode of origin of the Fraunhofer dark rays. Very important, however, was his demonstration of the compound nature of the spark-spectrum, which he showed to be made up of the spectrum of the metallic electrodes superposed upon that of the gas or gases across which the discharge passed.

It may here be useful—since without some clear ideas on the subject no proper understanding of recent astronomical progress is possible—to take a cursory view of the elementary principles of spectrum analysis. To many of our readers they are doubtless already familiar; but it is better to appear trite to some than obscure even to a few.

The spectrum, then, of a body is simply the light proceeding from it *spread out* by refraction[399] into a brilliant variegated band, passing from brownish-red through crimson, orange, yellow, green, and azure into dusky violet. The reason of this spreading-out or "dispersion" is that the various colours have different wave-lengths, and consequently meet with different degrees of retardation in traversing the denser medium of the prism. The shortest and quickest vibrations (producing the sensation we call "violet") are thrown farthest away from their original path—in other words, suffer the widest “deviation;” the longest and slowest (the red) travel much nearer to it. Thus the sheaf of rays which would otherwise combine into a patch of white light are separated through the divergence of their tracks after refraction by a prism, so as to form a tinted riband. This *visible* spectrum is prolonged *invisibly* at both ends by a long range of vibrations, either too rapid or too sluggish to affect the eye as light, but recognisable through their chemical and heating effects.

Now all incandescent solid or liquid substances, and even gases ignited under great pressure, give what is called a “continuous spectrum;” that is to say, the light derived from them is of every conceivable hue. Sorted out with the prism, its tints merge imperceptibly one into the other, uninterrupted by any dark spaces. No colours, in short, are missing. But gases and vapours rendered luminous by heat emit rays of only a few tints, which accordingly form an interrupted spectrum, usually designated as one of lines or bands. And since these rays are perfectly definite and characteristic—not being the same for any two substances—it is easy to tell what kind of matter is concerned in producing them. We may suppose that the inconceivably minute particles which by their rapid thrilling agitate the ethereal medium so as to produce light, are free to give out their peculiar tone of vibration only when floating apart from each other in gaseous form; but when crowded together into a condensed mass, the clear ring of the distinctive note is drowned, so to speak, in a universal molecular clang. Thus prismatic analysis has no power to identify individual kinds of matter, except when they present themselves as glowing vapours.

A spectrum is said to be “reversed” when lines previously seen bright on a dark background appear dark on a bright background. In this form it is equally characteristic of chemical composition with the “direct” spectrum, being due to *absorption*, as the latter is to *emission*. And absorption and emission are, by Kirchhoff’s law, strictly correlative. This is easily understood by the analogy of sound. For just as a tuning-fork responds to sound-waves of its own pitch, but remains indifferent to those of any other, so those particles of matter whose nature it is, when set swinging by heat, to vibrate a certain number of times in a second, thus giving rise to light of a particular shade of colour, appropriate those same vibrations, and those only, when transmitted past them,—or, phrasing it otherwise, are opaque to them, and transparent to all others.

It should further be explained that the *shape* of the bright or dark spaces in the spectrum has nothing whatever to do with the nature of the phenomena. The “lines” and “bands” so frequently spoken of are seen as such for no other reason than because the light forming them is admitted through a narrow, straight opening. Change that opening into a fine crescent or a sinuous curve, and the “lines” will at once appear as crescents or curves.

Resuming in a sentence what has been already explained, we find that the prismatic analysis of the heavenly bodies was founded upon three classes of facts: First, the unmistakable character of the light given by each different kind of glowing vapour; secondly, the identity of the light absorbed with the light emitted by each; thirdly, the coincidence observed between rays missing from the solar spectrum and rays absorbed by various terrestrial substances. Thus, a realm of knowledge, pronounced by Morinus[400] in the seventeenth century, and no less dogmatically by Auguste Comte[401] in the nineteenth, hopelessly out of reach of the human intellect, was thrown freely open, and the chemistry of the sun and stars took at once a leading place among the experimental sciences.

The immediate increase of knowledge was not the chief result of Kirchhoff's labours; still more important was the change in the scope and methods of astronomy, which, set on foot in 1852 by the detection of a common period affecting at once the spots on the sun and the magnetism of the earth, was extended and accelerated by the discovery of spectrum analysis. The nature of that change is concisely indicated by the heading of the present chapter; we would now ask our readers to endeavour to realise somewhat distinctly what is implied by the "foundation of astronomical physics."

Just three centuries ago, Kepler drew a forecast of what he called a "physical astronomy"—a science treating of the efficient causes of planetary motion, and holding the "key to the inner astronomy."[402] What Kepler dreamed of and groped after, Newton realized. He showed the beautiful and symmetrical revolutions of the solar system to be governed by a uniformly acting cause, and that cause no other than the familiar force of gravity, which gives stability to all our terrestrial surroundings. The world under our feet was thus for the first time brought into physical connection with the worlds peopling space, and a very tangible relationship was demonstrated as existing between what used to be called the "corruptible" matter of the earth and the "incorruptible" matter of the heavens.

This process of unification of the cosmos—this levelling of the celestial with the sublunary—was carried no farther until the fact unexpectedly emerged from a vast and complicated mass of observations, that the magnetism of the earth is subject to subtle influences, emanating, certainly from some, and presumably from all of the heavenly bodies; the inference being thus rendered at least plausible, that a force not less universal than gravity itself, but with whose modes of action we are as yet unacquainted, pervades the universe, and forms, it might be said, an intangible bond of sympathy between its parts. Now for the investigation of this influence two roads are open. It may be pursued by observation either of the bodies from which it proceeds, or of the effects which it produces—that is to say, either by the astronomer or by the physicist, or, better still, by both concurrently. Their acquisitions are mutually profitable; nor can either be considered as independent of the other. Any important accession to knowledge respecting the sun, for example, may be expected to cast a reflected light on the still obscure subject of terrestrial magnetism; while discoveries in magnetism or its *alter ego* electricity must profoundly affect solar inquiries.

The establishment of the new method of spectrum analysis drew far closer this alliance between celestial and terrestrial science. Indeed, they have come to merge so intimately one into the other, that it is no easier to trace their respective boundaries than it is to draw a clear dividing-line between the animal and vegetable kingdoms. Yet up to the middle of the last century, astronomy, while maintaining her strict union with mathematics, looked with indifference on the rest of the sciences; it was enough that she possessed the telescope and the calculus. Now the materials for her inductions are supplied by the chemist, the electrician, the inquirer into the most recondite mysteries of light and the molecular constitution of matter. She is concerned with what the geologist, the meteorologist, even the biologist, has to say; she can afford to close her ears to no new truth of the physical order. Her position of lofty isolation has been exchanged for one of community and mutual aid. The astronomer has become, in the highest sense of the term, a physicist; while the physicist is bound to be something of an astronomer.

This, then, is what is designed to be conveyed by the "foundation of astronomical or cosmical physics." It means the establishment of a science of Nature whose conclusions are not only presumed by analogy, but are ascertained by observation, to be valid wherever light can travel and gravity is obeyed—a science by which the nature of the stars can be studied upon the earth, and the nature of the earth can be made better known by study of the stars—a science, in a word, which is, or aims at being, one and universal, even as Nature—the visible reflection of the invisible highest Unity—is one and universal.

It is not too much to say that a new birth of knowledge has ensued. The astronomy so signally promoted by Bessel[403]—the astronomy placed by Comte[404] at the head of the hierarchy of the physical sciences—was the science of the *movements* of the heavenly bodies. And there were those who began to regard it as a science which, from its very perfection, had ceased to be interesting—whose tale of discoveries was told, and whose farther advance must be in the line of minute technical improvements, not of novel and stirring disclosures. But the science of the *nature* of the heavenly bodies is one only in the beginning of its career. It is full of the audacities, the inconsistencies, the imperfections, the possibilities of youth. It promises everything; it has already performed much; it will doubtless perform much more. The means at its disposal are vast and are being daily augmented. What has so far been secured by them it must now be our task to extricate from more doubtful surroundings and place in due order before our readers.

FOOTNOTES:

[347] Wolf, *Gesch. der Astr.*, p. 655.

[348] Manuel Johnson, *Mem. R.A.S.*, vol. xxvi., p. 197.

[349] *Astronomie Théorique et Pratique*, t. iii., p. 20.

[350] Wolf, *Gesch. der Astr.*, p. 654.

[351] *Month. Not.*, vol. xvii., p. 241.

[352] *Mem. R.A.S.*, vol. xxvi., p. 200.

[353] *Astr. Nach.*, No. 495.

[354] Gehler's *Physikalisches Wörterbuch*, art. *Sonnenflecken*, p. 851.

[355] *Zweite Abth.*, p. 401.

[356] *Annalen der Physik* (Poggendorff's), Bd. lxxxiv., p. 580.

[357] *Phil. Trans.*, vol. cxlii., p. 103.

[358] *Mittheilungen der Naturforschenden Gesellschaft*, 1852, p. 183.

[359] *Archives des Sciences*, t. xxi., p. 194.

[360] *Neue Untersuchungen*, *Mitth. Naturf. Ges.*, 1852, p. 249.

[361] *Phil. Trans.*, vol. xci., p. 316.

[362] Evidence of an eleven-yearly fluctuation in the price of food-grains in India was collected some years ago by Mr. Frederick Chambers. *Nature*, vol. xxxiv., p. 100.

[363] *Bibl. Un. de Genève*, t. li., p. 336.

[364] *Neue Untersuchungen*, p. 269.

[365] *Die Sonne und ihre Flecken*, p. 30. Arago was the first who attempted to decide the question by keeping, through a series of years, a parallel register of sun-spots and weather; but the data regarding the solar condition amassed at the Paris Observatory from 1822 to 1830 were not sufficiently precise to support any inference.

[366] *Phil. Trans.*, vol. xxix., p. 421.

[367] *Ibid.*, vols. cxliii., p. 558, cxlvi., p. 505.

[368] *Observations on Light and Colours*, p. 35.

[369] *Phil. Trans.*, vol. lxxv., p. 190.

[370] *Denkschriften* (Munich. Ac. of Sc.), 1814, 1815, Bd. v., p. 197.

[371] *Edinburgh Journal of Science*, vol. v., p. 77. See also *Phil. Mag.*, Feb., 1834, vol. iv., p. 112.

[372] *Ed. Phil. Trans.*, vol. xxi., p. 411.

[373] *On the Absorption of Light by Coloured Media*, *Ed. Phil. Trans.*, vol. ix., p. 445 (1823).

[374] *Phil. Mag.*, vol. xxvii, (ser. iii.), p. 81.

[375] *Report Brit. Ass.*, 1835, p. 11 (pt. ii.). *Electrodes* are the terminals from one to the other of which the electric spark passes, volatilising and rendering incandescent in its transit some particles of their substance, the characteristic light of which accordingly flashes out in the spectrum.

[376] *Phil. Mag.*, vol. xx., p. 93.

[377] *Annalen der Physik*, Bd. cxiii., p. 357.

[378] *Phil. Trans.*, vol. xcii., p. 378.

[379] *Denkschriften*, Bd. v., p. 202.

[380] *Ibid.*, p. 220; *Edin. Jour. of Science*, vol. viii., p. 9.

[381] *Denkschriften*, Bd. v., p. 222.

[382] *Arch. des Sciences*, 1849, p. 43.

[383] *Phil. Trans.*, vol. cl., p. 159, *note*.

[384] *Ed. Phil. Trans.*, vol. xii., p. 528.

[385] *Phil. Trans.*, vol. cxxvi., p. 453. "I conceive," he says, "that this result proves decisively that the sun's atmosphere has nothing to do with the production of this singular phenomenon" (p. 455). And Brewster's well-founded opinion that it had much to do with it was thereby, in fact, overthrown.

[386] *Monatsberichte*, Berlin, 1859, p. 664.

[387] *Abhandlungen*, Berlin, 1861, pp. 80, 81.

[388] *Ibid.*, 1861, p. 77; *Annalen der Physik*, Bd. cxix., p. 275. A similar conclusion, reached by Balfour Stewart in 1858, for heat-rays (*Ed. Phil. Trans.*, vol. xxii., p. 13), was, in 1860, without previous knowledge of Kirchhoff's work, extended to light (*Phil. Mag.*, vol. xx., p. 534); but his experiments wanted the precision of those executed at Heidelburg.

[389] *Miscellaneous Works*, vol. i., p. 189.

[390] *Ed. Phil. Trans.*, vol. ix., p. 458.

[391] *Ibid.*, vol. xii., p. 519.

[392] *Quart. Jour. Chem. Soc.*, vol. x. p. 79.

[393] A facsimile accompanied Sir H. Roscoe's translation of Kirchhoff's "Researches on the Solar Spectrum" (London, 1862-63).

[394] Estimated by Kirchhoff's at a *trillion to one*. *Abhandl.*, 1861, p. 79.

[395] *Phil. Mag.*, vol. xxvii. (3rd series), p. 90.

[396] *L'Institut*, Feb. 7, 1849, p. 45; *Phil. Mag.*, vol. xix. (4th series), p. 193.

[397] *Ann. d. Phys.*, vol. cxviii., p. 110.

[398] *Phil. Mag.*, vol. ix. (4th series), p. 327.

[399] Spectra may be produced by *diffraction* as well as by *refraction*; but we are here only concerned with the subject in its simplest aspect.

[400] *Astrologia Gallica* (1661), p. 189.

[401] *Pos. Phil.*, vol. i., pp. 114, 115 (Martineau's trans.).

[402] *Proem Astronomiæ Pars Optica* (1640), *Op.*, t. ii.

[403] *Pop. Vorl.*, pp. 14, 19, 408.

[404] *Pos. Phil.*, p. 115.

CHAPTER II

SOLAR OBSERVATIONS AND THEORIES

The zeal with which solar studies have been pursued during the last half century has already gone far to redeem the neglect of the two preceding ones. Since Schwabe's discovery was published in 1851, observers have multiplied, new facts have been rapidly accumulated, and the previous comparative quiescence of thought on the great subject of the constitution of the sun, has been replaced by a bewildering variety of speculations, conjectures, and more or less justifiable inferences. It is satisfactory to find this novel impulse not only shared, but to a large extent guided, by our countrymen.

William Rutter Dawes, one of many clergymen eminent in astronomy, observed, in 1852, with the help of a solar eye-piece of his own devising, some curious details of spot-structure.[405] The umbra—heretofore taken for the darkest part of the spot—was seen to be suffused with a mottled, nebulous illumination, in marked contrast with the striated appearance of the penumbra; while through this "cloudy stratum" a "black opening" permitted the eye to divine farther unfathomable depths beyond. The *hole* thus disclosed—evidently the true nucleus—was found to be present in all considerable, as well as in many small maculæ.

Again, the whirling motions of some of these objects were noticed by him. The remarkable form of one sketched at Wateringbury, in Kent, January 17, 1852, gave him the means of detecting and measuring a rotatory movement of the whole spot round the black nucleus at the rate of 100 degrees in six days. "It appeared," he said, "as if some prodigious ascending force of a whirlwind character, in bursting through the cloudy stratum and the two higher and luminous strata, had given to the whole a movement resembling its own."[406] An interpretation founded, as is easily seen, on the Herschelian theory, then still in full credit.

An instance of the same kind was observed by Mr. W. R. Birt in 1860,[407] and cyclonic movements are now a recognised feature of sun-spots. They are, however, as Father Secchi[408] concluded from his long experience, but temporary and casual. Scarcely three per cent. of all spots visible exhibit the spiral structure which should invariably result if a conflict of opposing, or the friction of unequal, currents were essential, and not merely incidental to their origin. A whirlpool phase not unfrequently accompanies their formation, and may be renewed at periods of recrudescence or dissolution; but it is both partial and inconstant, sometimes affecting only one side of a spot, sometimes slackening gradually its movement in one direction, to resume it, after a brief pause, in the opposite. Persistent and uniform notions, such as the analogy of terrestrial storms would absolutely require, are not to be found. So that the "cyclonic theory" of sun-spots, suggested by Herschel in 1847,[409] and urged, from a different point of view, by Faye in 1872, may be said to have completely broken down.

The drift of spots over the sun's surface was first systematically investigated by Carrington, a self-constituted astronomer, gifted with the courage and the instinct of thoughtful labour.

Born at Chelsea in May, 1826, Richard Christopher Carrington entered Trinity College, Cambridge, in 1844. He was intended for the Church, but Professor Challis's lectures diverted him to astronomy, and he resolved, as soon as he had taken his degree, to prepare, with all possible diligence, to follow his new vocation. His father, who was a brewer on a large scale at Brentford, offered no opposition; ample means were at his disposal; nevertheless, he chose to serve an apprenticeship of three years as observer in the University of Durham, as though his sole object had been to earn a livelihood. He quitted the post only when he found that its restricted opportunities offered no farther prospect of self-improvement.

He now built an observatory of his own at Redhill in Surrey, with the design of completing Bessel's and Argelander's survey of the northern heavens by adding to it the circumpolar stars omitted from their view. This project, successfully carried out between 1854 and 1857, had another and still larger one superposed upon it before it had even begun to be executed. In 1852, while the Redhill Observatory was in course of erection, the discovery of the coincidence between the sun-spot and magnetic periods was announced. Carrington was profoundly interested, and devoted his enforced leisure to the examination of records, both written and depicted, of past solar observations. Struck with their fragmentary and inconsistent character, he resolved to "appropriate," as he said, by "close and methodical research," the eleven-year period next ensuing.[410] He calculated rightly that he should have the field pretty nearly to himself; for many reasons conspire to make public observatories slow in taking up new subjects, and amateurs with freedom to choose, and means to treat them effectually, were scarcer then than they are now.

The execution of this laborious task was commenced November 9, 1853. It was intended to be merely a *parergon*—a "second subject," upon which daylight energies might be spent, while the hours of night were reserved for cataloguing those stars that "are bereft of the baths of ocean." Its results, however, proved of the highest interest, although the vicissitudes of life barred the completion, in its full integrity, of the original design. By the death, in 1858, of the elder Carrington, the charge of the brewery devolved upon his son; and eventually absorbed so much of his care that it was found advisable to bring the solar observations to a premature close, on March 24, 1861.

His scientific life may be said to have closed with them. Attacked four years later with severe, and, in its results, permanent illness, he disposed of the Brentford business, and withdrew to Churt, near Farnham, in Surrey. There, in a lonely spot, on the top of a detached conical hill known as the "Devil's Jump," he built a second observatory, and erected an instrument which he was no longer able to use with pristine effectiveness; and there, November 27, 1875, he died of the rupture of a blood vessel on the brain, before he had completed his fiftieth year.[411]

His observations of sun-spots were of a geometrical character. They concerned positions and movements, leaving out of sight physical peculiarities. Indeed, the prudence with which he limited his task to what came strictly within the range of his powers to accomplish, was one of Carrington's most valuable qualities. The method of his observations, moreover, was chosen with the same practical sagacity as their objects. As early as 1847, Sir John Herschel had recommended the daily self-registration of sun-spots,[412] and he enforced the suggestion, with more immediate prospect of success, in 1854.[413] The art of celestial photography, however, was even then in a purely tentative stage, and Carrington wisely resolved to waste no time on dubious experiments, but employ the means of registration and measurement actually at his command. These were very simple, yet very effective. To the "helioscope" employed by Father Scheiner[414] two centuries and a quarter earlier, a species of micrometer was added. The image of the sun was projected upon a screen by means of a firmly-clamped telescope, in the focus of which were placed two cross-wires forming angles of 45° with the meridian. The six instants were then carefully noted at which these were met by the edges of the disc as it traversed the screen, and by the nucleus of the spot to be measured.[415] A short process of calculation then gave the exact position of the spot as referred to the sun's centre.

From a series of 5,290 observations made in this way, together with a great number of accurate drawings, Carrington derived conclusions of great importance on each of the three points which he had proposed to himself to investigate. These were: the law of the sun's rotation, the existence and direction of systematic currents, and the distribution of spots on the solar surface.

Grave discrepancies were early perceived to exist between determinations of the sun's rotation by different observers. Galileo, with "comfortable generality," estimated the period at "about a lunar month";[416] Scheiner, at twenty-seven days.[417] Cassini, in 1678, made it 25·58; Delambre, in 1775, no more than twenty-five days. Later inquiries brought these divergences within no more tolerable limits. Laugier's result of 25·34 days—obtained in 1841—enjoyed the highest credit, yet it differed widely in one direction from that of Böhm (1852), giving 25·52 days, and in the other from that of Kysæus (1846), giving 25·09 days. Now the cause of these variations was really obvious from the first, although for a long time strangely overlooked. Scheiner pointed out in 1630 that different spots gave different periods, adding the significant remark that one at a distance from the solar equator revolved more slowly than those nearer to it.[418] But the hint was wasted. For upwards of two centuries ideas on the subject were either retrograde or stationary. What were called the "proper motions" of spots were, however, recognised by Schröter,[419] and utterly baffled Laugier,[420] who despaired of obtaining any concordant result as to the sun's rotation except by taking the mean of a number of discordant ones. At last, in

1855, a valuable course of observations made at Capo di Monte, Naples, in 1845-6, enabled C. H. F. Peters[421] to set in the clearest light the insecurity of determinations based on the assumption of fixity in objects plainly affected by movements uncertain both in amount and direction.

Such was the state of affairs when Carrington entered upon his task. Everything was in confusion; the most that could be said was that the confusion had come to be distinctly admitted and referred to its true source. What he discovered was this: that the sun, or at least the outer shell of the sun visible to us, has *no single period of rotation*, but drifts round, carrying the spots with it, at a rate continually accelerated from the poles to the equator. In other words, the time of axial revolution is shortest at the equator and lengthens with increase of latitude. Carrington devised a mathematical formula by which the rate or "law" of this lengthening was conveniently expressed; but it was a purely empirical one. It was a concise statement, but implied no physical interpretation. It summarised, but did not explain the facts. An assumed "mean period" for the solar rotation of 25·38 days (twenty-five days nine hours, very nearly), was thus found to be *actually* conformed to only in two parallels of solar latitude (14° north and south), while the equatorial period was slightly less than twenty-five, and that of latitude 50° rose to twenty-seven days and a half.[422] These curious results gave quite a new direction to ideas on solar physics.

The other two "elements" of the sun's rotation were also ascertained by Carrington with hitherto unattained precision. He fixed the inclination of its axis to the ecliptic at 82° 45′; the longitude of the ascending node at 73° 40′ (for the epoch 1850 A.D.). These data—which have scarcely yet been improved upon—suffice to determine the position in space of the sun's equator. Its north pole is directed towards a star in the coils of the Dragon, midway between Vega and the Pole-star; its plane intersects that of the earth's orbit in such a way that our planet finds itself in the same level on or about the 3rd of June and the 5th of December, when any spots visible on the disc cross it in apparently straight lines. At other times, the paths pursued by them seem curved—downward (to an observer in the northern hemisphere) between June and December, upward between December and June.

A singular peculiarity in the distribution of sun-spots emerged from Carrington's studies at the time of the minimum of 1856. Two broad belts of the solar surface, as we have seen, are frequented by them, of which the limits may be put at 6° and 35° of north and south latitude. Individual equatorial spots are not uncommon, but nearer to the poles than 35° they are a rare exception. Carrington observed—as an extreme instance—in July, 1858, one in south latitude 44°; and Peters, in June, 1846, watched, during several days, a spot in 50° 24′ north latitude. But beyond this no true macula has ever been seen; for Lahire's reported observation of one in latitude 70° is now believed to have had its place on the solar globe erroneously assigned; and the "veiled spots" described by Trouvelot in 1875[423] as occurring within 10° of the pole can only be regarded as, at the most, the same kind of disturbance in an undeveloped form.

But the novelty of Carrington's observations consisted in the detection of certain changes in distribution concurrent with the progress of the eleven-year period. As the minimum approached, the spot-zones contracted towards the equator, and there finally vanished; then, as if by a fresh impulse, spots suddenly reappeared in high latitude, and spread downwards with the development of the new phase of activity. Scarcely had this remark been made public,[424] when Wolf[425] found a confirmation of its general truth in Böhm's observations during the years 1833-36; and a perfectly similar behaviour was noted both by Spörer and Secchi at the minimum epoch of 1867. The ensuing period gave corresponding indications; and it may now be looked upon as established that the spot-zones close in towards the equator with the advance of each cycle, their activity culminating, as a rule, in a mean latitude of about 16°, and expiring when it is reduced to 6°. Before this happens, however, a completely new disturbance will have manifested itself some 35° north and south of the equator, and will have begun to travel over the same course as its predecessor. Each series of sun-spots is thus, to some extent, overlapped by the succeeding one; so that while the average interval from one maximum to the next is eleven years, the period of each distinct wave of agitation is twelve or fourteen.[426] Curious evidence of the retarded character of the maximum of 1883-4 was to be found in the unusually low latitude of the spot-zones when it occurred. Their movement downward having gone on regularly while the crisis was postponed, its final symptoms were hence displaced locally as well as in time. The "law of zones" was duly obeyed at the minima of 1890[427] and 1901, and Spörer found evidence of conformity to it so far back as 1619.[428] His researches, however, also showed that it was in abeyance during some seventy years previously to 1716, during which period sun-spots remained persistently scarce, and auroral displays were feeble and infrequent even in high northern latitudes. An unaccountable suspension of solar activity is, in fact, indicated.[429]

Gustav Spörer, born at Berlin in 1822, began to observe sun-spots with the view of assigning the law of solar rotation in December, 1860. His assiduity and success with limited means attracted attention, and a Government endowment was procured for his little solar observatory at Anclam, in Pomerania, the Crown Prince (afterwards Emperor Frederick) adding a five-inch refractor to its modest equipment. Unaware of Carrington's discovery (not made known until January, 1859), he arrived at and published, in June, 1861,[430] a similar conclusion as to the equatorial quickening of the sun's movement on its axis. Appointed observer in the new Astrophysical establishment at Potsdam in 1874, he continued his sun-spot determinations there for twenty years, and died July 7, 1895.

The time had now evidently come for a fundamental revision of current notions respecting the nature of the sun. Herschel's theory of a cool, dark, habitable globe, surrounded by, and protected against, the radiations of a luminous and heat-giving envelope, was shattered by the first *dicta* of spectrum analysis. Traces of it may be found for a few years subsequent to 1859,[431] but they are obviously survivals from an earlier order of ideas, doomed to speedy extinction. It needs only a moment's consideration of the meaning at last found for the Fraunhofer lines to see the incompatibility of the new facts with the old conceptions. They implied not only the presence near the sun, as glowing vapours, of bodies highly refractory to heat, but that these glowing vapours formed the relatively cool envelope of a still hotter internal mass. Kirchhoff, accordingly, included in his great memoir "On the Solar Spectrum," read before the Berlin Academy of Sciences, July 11, 1861, an exposition of the views on the subject to which his memorable investigations had led him. They may be briefly summarised as follows:

Since the body of the sun gives a continuous spectrum, it must be either solid or liquid, [432] while the interruptions in its light prove it to be surrounded by a complex atmosphere of metallic vapours, somewhat cooler than itself. Spots are simply clouds due to local depressions of temperature, differing in no respect from terrestrial clouds except as regards the kinds of matter composing them. These *sun-clouds* take their origin in the zones of encounter between polar and equatorial currents in the solar atmosphere.

This explanation was liable to all the objections urged against the "cumulus theory" on the one hand, and the "trade-wind theory" on the other. Setting aside its propounder, it was consistently upheld perhaps by no man eminent in science except Spörer; and his advocacy of it proved ineffective to secure its general adoption.

M. Faye, of the Paris Academy of Sciences, was the first to propose a coherent scheme of the solar constitution covering the whole range of new discovery. The fundamental ideas on the subject now in vogue here made their first connected appearance. Much, indeed, remained to be modified and corrected; but the transition was finally made from the old to the new order of thought. The essence of the change may be conveyed in a single sentence. The sun was thenceforth regarded, not as a mere heated body, or—still more remotely from the truth—as a cool body unaccountably spun round with a cocoon of fire, but as a vast *heat-radiating machine*. The terrestrial analogy was abandoned in one more particular besides that of temperature. The solar system of circulation, instead of being adapted, like that of the earth, to the distribution of heat received from without, was seen to be directed towards the transportation towards the surface of the heat contained within. Polar and equatorial currents, tending to a purely superficial equalisation of temperature, were replaced by vertical currents bringing up successive portions of the intensely heated interior mass, to contribute their share in turn to the radiation into space which might be called the proper function of a sun.

Faye's views, which were communicated to the Academy of Sciences, January 16, 1865, [433] were avowedly based on the anomalous mode of solar rotation discovered by Carrington. This may be regarded either as an acceleration increasing from the poles to the equator, or as a retardation increasing from the equator to the poles, according to the rate of revolution we choose to assume for the unseen nucleus. Faye preferred to consider it a retardation produced by ascending currents continually left behind as the sphere widened in which the matter composing them was forced to travel. He further supposed that the depth from which these vertical currents rose, and consequently the amount of retardation effected by their ascent to the surface, became progressively greater as the poles were approached, owing to the considerable flattening of the spheroidal surface from which they started;[434] but the adoption of this expedient has been shown to involve inadmissible consequences.

The extreme internal mobility betrayed by Carrington's and Spörer's observations led to the inference that the matter composing the sun was mainly or wholly gaseous. This had already been suggested by Father Secchi[435] a year earlier, and by Sir John Herschel in April, 1864;[436] but it first obtained general currency through Faye's more elaborate presentation. A physical basis was afforded for the view by Cagniard de la Tour's experiments in 1822,[437] proving that, under conditions of great heat and pressure, the vaporous state was compatible with a very considerable density. The position was strengthened when Andrews showed, in 1869,[438] that above a fixed limit of temperature, varying for different bodies, true liquefaction is impossible, even though the pressure be so tremendous as to retain the gas within the same space that enclosed the liquid. The opinion that the mass of the sun is gaseous now commands a very general assent; although the gaseity admitted is of such a nature as to afford the consistence rather of honey or pitch than of the aeriform fluids with which we are familiar.

On another important point the course of subsequent thought was powerfully influenced by Faye's conclusions in 1865. Arago somewhat hastily inferred from experiments with the polariscope the wholly gaseous nature of the visible disc of the sun. Kirchhoff, on the contrary, believed (erroneously, as we now know) that the brilliant continuous spectrum derived from it proved it to be a white-hot solid or liquid. Herschel and Secchi[439] indicated a cloud-like structure as that which would best harmonise the whole of the evidence at command. The novelty introduced by Faye consisted in regarding the photosphere no longer "as a defined surface, in the mathematical sense, but as a limit to which, in the general fluid mass, ascending currents carry the physical or chemical phenomena of incandescence."[440] Uprushing floods of mixed vapours with strong affinities—say of calcium or sodium and oxygen—at last attain a region cool enough to permit their combination; a fine dust of solid or liquid compound particles (of lime or soda, for example) there collects into the photospheric clouds, and descending by its own weight in torrents of incandescent rain, is dissociated by the fierce heat below, and replaced by ascending and combining currents of similar constitution.

This first attempt to assign the part played in cosmical physics by chemical affinities was marked by the importation into the theory of the sun of the now familiar phrase *dissociation*. It is indeed tolerably certain that no such combinations as those contemplated by Faye occur at the photospheric level, since the temperature there must be enormously higher than would be needed to reduce all metallic earths and oxides; but molecular changes of some kind, dependent perhaps in part upon electrical conditions, in part upon the effects of radiation into space, most likely replace them. The conjecture was emitted by Dr. Johnstone Stoney in 1867[441] that the photospheric clouds are composed of carbon-particles precipitated from their mounting vapour just where the temperature is lowered by expansion and radiation to the boiling-point of that substance. But this view, though countenanced by Ångström,[442] and advocated by Hastings of Baltimore,[443] and other authorities,[444] is open to grave objections.[445]

In Faye's theory, sun-spots were regarded as simply breaks in the photospheric clouds, where the rising currents had strength to tear them asunder. It followed that they were regions of increased heat—regions, in fact, where the temperature was too high to permit the occurrence of the precipitations to which the photosphere is due. Their obscurity was attributed, as in Dr. Brester's more recent *Théorie du Soleil*, to deficiency of emissive power. Yet here the verdict of the spectroscope is adverse and irreversible.

After every deduction, however, has been made, we still find that several ideas of permanent value were embodied in this comprehensive sketch of the solar constitution. The principal of these were; first, that the sun is a mainly gaseous body; secondly, that its stores of heat are rendered available at the surface by means of vertical convection-currents—by the bodily transport, that is to say, of intensely hot matter upward, and of comparatively cool matter downward; thirdly, that the photosphere is a surface of condensation, forming the limit set by the cold of space to this circulating process, and that a similar formation must attend, at a certain stage, the cooling of every cosmical body.

To Warren de la Rue belongs the honour of having obtained the earliest results of substantial value in celestial photography. What had been done previously was interesting in the way of promise, but much could not be claimed for it as actual performance. Some "pioneering experiments" were made by Dr. J. W. Draper of New York in 1840, resulting in the production of a few "moon-pictures" one inch in diameter;[446] but slight encouragement was derived from them, either to himself or others. Bond of Cambridge (U.S.), however, secured in 1850 with the Harvard 15-inch refractor that daguerreotype of the moon with which the career of extra-terrestrial photography may be said to have formally opened. It was shown in London at the Great Exhibition of 1851, and determined the direction of De la Rue's efforts. Yet it did little more than prove the art to be a possible one.

Warren de la Rue was born in Guernsey in 1815, and died in London April 19, 1889. Educated at the École Sainte-Barbe in Paris, he made a large fortune as a paper manufacturer in England, and thus amply and early provided the material supplies for his scientific campaign. Towards the end of 1853 he took some successful lunar photographs. They were remarkable as the first examples of the application to astronomical light-painting of the collodion process, invented by Archer in 1851; and also of the use of reflectors (De la Rue's was one of thirteen inches, constructed by himself) for that kind of work. The absence of a driving apparatus was, however, very sensibly felt; the difficulty of moving the instrument by hand so as accurately to follow the moon's apparent motion being such as to cause the discontinuance of the experiments until 1857, when the want was supplied. De la Rue's new observatory, built in that year at Cranford, was expressly dedicated to celestial photography; and there he applied to the heavenly bodies the stereoscopic method of obtaining relief, and turned his attention to the delicate business of photographing the sun.

A solar daguerreotype was taken at Paris, April 2, 1845,[447] by Foucault and Fizeau, acting on a suggestion from Arago. But the attempt, though far from being unsuccessful, does not, at that time, seem to have been repeated. Its great difficulty consisted in the enormous light-power of the object to be represented, rendering an inconceivably short period of exposure indispensable, under pain of getting completely "burnt-up" plates. In 1857 De la Rue was commissioned by the Royal Society to construct an instrument specially adapted to the purpose for the Kew Observatory. The resulting "photoheliograph" may be described as a small telescope (of 3-1/2 inches aperture and 50 focus), with a plate-holder at the eye-end, guarded in front by a spring-slide, the rapid movement of which across the field of view secured for the sensitive plate a virtually instantaneous exposure. By its means the first solar light-pictures of real value were taken, and the autographic record of the solar condition recommended by Sir John Herschel was commenced and continued at Kew during fourteen years—1858-72. The work of photographing the sun is now carried on in every quarter of the globe, from Mauritius to Massachusetts, and the days are few indeed on which the self-betrayal of the camera can be evaded by our chief luminary. In the year 1883 the incorporation of Indian with Greenwich pictures afforded a record of the state of the solar surface on 340 days; and 364 were similarly provided for in 1897 and 1899.

The conclusions arrived at by photographic means at Kew were communicated to the Royal Society in a series of papers drawn up jointly by De la Rue, Balfour Stewart, and Benjamin Loewy, in 1865 and subsequent years. They influenced materially the progress of thought on the subject they were concerned with.

By its rotation the sun itself offers opportunities for bringing the stereoscope to bear upon it. Two pictures, taken at an interval of twenty-six minutes, show just the amount of difference needed to give, by their combination, the maximum effect of solidity.[448] De la Rue thus obtained, in 1861, a stereoscopic view of a sun-spot and surrounding faculæ, representing the various parts in their true mutual relations. "I have ascertained in this way," he wrote,[449] "that the faculæ occupy the highest portions of the sun's photosphere, the spots appearing like holes in the penumbræ, which appeared lower than the regions surrounding them; in one case, parts of the faculæ were discovered to be sailing over a spot apparently at some considerable height above it." Thus Wilson's inference as to the depressed nature of spots received, after the lapse of not far from a century, proof of the most simple, direct, and convincing kind. A careful application of Wilson's own geometrical test gave results only a trifle less decisive. Of 694 spots observed, 78 per cent. showed, as they traversed the disc, the expected effects of perspective;[450] and their absence in the remaining 22 per cent. might be explained by internal commotions producing irregularities of structure. The absolute depth of spot-cavities—at least of their sloping sides—was determined by Father Secchi through measurement of the "parallax of profundity"[451]—that is, of apparent displacements attendant on the sun's rotation, due to depression below the sun's surface. He found that in every case it fell short of 4,000 miles, and averaged not more than 1,321, corresponding, on the terrestrial scale, to an excavation in the earth's crust of 1-1/5 miles. Of late, however, the reality of even this moderate amount of depression has been denied. Mr. Howlett's persevering observations, extending over a third of a century, the results of which were presented to the Royal Astronomical Society in December, 1894,[452] availed to shatter the consensus of opinion which had so long been maintained on the subject of spot-structure.[453] It has become impossible any longer to hold that it is uniformly cavernous; and what seem like actually protruding umbræ are occasionally vouched for on unimpeachable authority.[454] We can only infer that the forms of sun-spots are really more various than had been supposed; that they are peculiarly subject to disturbance; and that the level of the nuclei may rise and fall during the phases of commotion, like lavas within volcanic craters.

The opinion of the Kew observers as to the nature of such disturbances was strongly swayed by another curious result of the "statistical method" of inquiry. They found that of 1,137 instances of spots accompanied by faculæ, 584 had those faculæ chiefly or entirely on the left, 508 showed a nearly equal distribution, while 45 only had faculous appendages mainly on the right side.[455] Now the rotation of the sun, as we see it, is performed from left to right; so that the marked tendency of the faculæ was a lagging one. This was easily accounted for by supposing the matter composing them to have been flung upwards from a considerable depth, whence it would reach the surface with the lesser *absolute* velocity belonging to a smaller circle of revolution, and would consequently fall behind the cavities or "spots" formed by its abstraction. An attempt, it is true, made by M. Wilsing at Potsdam in 1888[456] to determine the solar rotation from photographs of faculæ had an outcome inconsistent with this view of their origin. They unexpectedly gave a uniform period. No trace of the retardation poleward from the equator, shown by the spots, could be detected in their movements. But the experiment was obviously inconclusive;[457] and M. Stratonoff's[458] repetition of it with ampler materials gave a full assurance that faculæ rotate like spots in periods lengthening as latitude augments.

The ideas of M. Faye were, on two fundamental points, contradicated by the Kew investigators. He held spots to be regions of *uprush* and of heightened temperature; they believed their obscurity to be due to a *downrush* of comparatively cool vapours. Now M. Chacornac, observing, at Ville-Urbanne, March 6, 1865, saw floods of photospheric matter visibly precipitating themselves into the abyss opened by a great spot, and carrying with them small neighbouring maculæ.[459] Similar instances were repeatedly noted by Father Secchi, who considered the existence of a kind of *suction* in spots to be quite beyond question.[460] The tendency in their vicinity, to put it otherwise, is *centripetal*, not *centrifugal*; and this alone seems to negative the supposition of a central uprush.

A fresh witness was by this time at hand. The application of the spectroscope to the direct examination of the sun's surface dates from March 4, 1866, when Sir Norman Lockyer (to give him his present title) undertook an inquiry into the cause of the darkening in spots.[461] It was made possible by the simple device of throwing upon the slit of the spectroscope an *image* of the sun, any part of which could be subjected to special scrutiny, instead of, as had hitherto been done, admitting rays from every portion of his surface indiscriminately. The answer to the inquiry was prompt and unmistakable, and was again, in this case, adverse to the French theorist's view. The obscurations in question were found to be produced by no deficiency of emissive power, but by an increase of absorptive action. The background of variegated light remains unchanged, but more of it is stopped by the interposition of a dense mass of relatively cool vapours. The spectrum of a sun-spot is crossed by the same set of multitudinous dark lines, with some minor differences, visible in the ordinary solar spectrum. We must then conclude that the same vapours (speaking generally) which are dispersed over the unbroken solar surface are accumulated in the umbral cavity, the compression incident to such accumulation being betrayed by the thickening of certain lines of absorption. But there is also a general absorption, extending almost continuously from one end of the spot-spectrum to the other. Using, however, a spectroscope of exceptionally high dispersive power, Professor Young of Princeton, New Jersey, succeeded in 1883 in "resolving" the supposed continuous obscurity of spot-spectra into a countless multitude of fine dark lines set very close together.[462] Their structure was seen still more perfectly, about five years later, by M. Dunér,[463] Director of the Upsala Observatory, who traced besides some shadowy vestiges of the crowded doublets and triplets forming the array, from the spots on to the general solar surface. They cease to be separable in the blue part of the spectrum; and the ultra-violet radiations of spots show nothing distinctive.[464]

As to the movements of the constipated vapours forming spots, the spectroscope is also competent to supply information. The principle of the method by which it is procured will be explained farther on. Suffice it here to say that the transport, at any considerable velocity, to or from the eye of the gaseous material giving bright or dark lines, can be measured by the displacement of such lines from their previously known normal positions. In this way movements have been detected in or above spots of enormous rapidity, ranging up to 320 *miles per second*. But the result, so far, has been to negative the ascription to them of any systematic direction. Uprushes and downrushes are doubtless, as Father Cortie remarks,[465] "correlated phenomena in the production of a sun-spot"; but neither seem to predominate as part of its regular internal economy.

The same kind of spectroscopic evidence tells heavily against a theory of sun-spots started by Faye in 1872. He had been foremost in pointing out that the observations of Carrington and Spörer absolutely forbade the supposition that any phenomenon at all resembling our trade-winds exists in the sun. They showed, indeed, that beyond the parallels of 20° there is a general tendency in spots to a slow poleward displacement, while within that zone they incline to approach the equator; but their "proper movements" gave no evidence of uniformly flowing currents in latitude. The systematic drift of the photosphere is strictly a drift in longitude; its direction is everywhere parallel to the equator. This fact being once clearly recognised, the "solar tornado" hypothesis at once fell to pieces; but M. Faye[466] perceived another source of vorticose motion in the unequal rotating velocities of contiguous portions of the photosphere. The "pores" with which the whole surface of the sun is studded he took to be the smaller eddies resulting from these inequalities; the spots to be such eddies developed into whirlpools. It only needs to thrust a stick into a stream to produce the kind of effect designated. And it happens that the differences of angular movement adverted to attain a maximum just about the latitudes where spots are most frequent and conspicuous.

There are, however, grave difficulties in identifying the two kinds of phenomena. One (already mentioned) is the total absence of the regular swirling motion—in a direction contrary to that of the hands of a watch north of the solar equator, in the opposite sense south of it—which should impress itself upon every lineament of a sun-spot if the cause assigned were a primary producing, and not merely (as it possibly may be) a secondary determining one. The other, pointed out by Young,[467] is that the cause is inadequate to the effect. The difference of movement, or *relative drift*, supposed to occasion such prodigious disturbances, amounts, at the utmost, for two portions of the photosphere 123 miles apart, to about five yards a minute. Thus the friction of contiguous sections must be quite insignificant.

A view better justified by observation was urged by Secchi in and after the year 1872, and was presented in an improved form by Professor Young in his excellent little book on *The Sun*, published in 1882.[468] Spots are manifestly associated with violent eruptive action, giving rise to the faculæ and prominences which usually garnish their borders. It is accordingly contended that upon the withdrawal of matter from below by the flinging up of a prominence must ensue a sinking-in of the surface, into which the partially cooled erupted vapours rush and settle, producing just the kind of darkening by increased absorption told of by the spectroscope. Round the edges of the cavity the rupture of the photospheric shell will form lines of weakness provocative of further eruptions, which will, in their turn, deepen and enlarge the cavity. The phenomenon thus tends to perpetuate itself, until equilibrium is at last restored by internal processes. A sun-spot might then be described as an inverted terrestrial volcano, in which the outbursts of heated matter take place on the borders instead of at the centre of the crater, while the cooled products gather in the centre instead of at the borders.

But on the earth, the solid crust forcibly represses the steam gathering beneath until it has accumulated strength for an explosion, while there is no such restraining power that we know of in the sun. Zöllner, indeed, adapted his theory of the solar constitution to the special purpose of procuring it; yet with very partial success, since almost every new fact has proved adverse to his assumptions. Volcanic action is essentially spasmodic. It implies habitual constraint varied by temporary outbreaks, inconceivable in a gaseous globe, such as we believe the sun to be.

If the "volcanic hypothesis" represented the truth, no spot could possibly appear without a precedent eruption. The real order of the phenomenon, however, is exceedingly difficult to ascertain; nor is it perhaps invariable. Although, in most cases, the "opening" shows first, that may be simply because it is more easily seen. According to Father Sidgreaves,[469] the disturbance has then already passed the incipient stage. He considers it indeed "highly probable that the preparatory sign of a new spot is always a small, bright patch of facula."

This sequence, if established, would be fatal to Lockyer's theory of sun-spots, communicated to the Royal Society, May 6, 1886,[470] and further developed some months later in his work on *The Chemistry of the Sun*. Spots are represented in it as incidental to a vast system of solar atmospheric circulation, starting with the polar out- and up-flows indicated by observations during some total eclipses, and eventuating in the plunge downward from great heights upon the photosphere of prodigious masses of condensed materials. From these falls result, primarily, spots; secondarily, through the answering uprushes in which chemical and mechanical forces co-operate, their girdles of flame-prominences. The evidence is, however, slight that such a circulatory flow as would be needed to maintain this supposed cycle of occurrences really prevails in the sun's atmosphere; and a similar objection applies to an "anticyclonic theory" (so to designate it) elaborated by Egon von Oppolzer in 1893.[471] August Schmidt's optical rationale of solar phenomena[472] was, on the other hand, a complete novelty, both in principle and development. Attractive to speculators from its recondite nature and far-reaching scope, it by no means commended itself to practical observers, intolerant of finding the all but palpable realities of their daily experience dealt with as illusory products of "circular refraction."

A singular circumstance has now to be recounted. On the 1st of September, 1859, while Carrington was engaged in his daily work of measuring the positions of sun-spots, he was startled by the sudden appearance of two patches of peculiarly intense light within the area of the largest group visible. His first idea was that a ray of unmitigated sunshine had penetrated the screen employed to reduce the brilliancy of the image; but, having quickly convinced himself to the contrary, he ran to summon an additional witness of an unmistakably remarkable occurrence. On his return he was disappointed to find the strange luminous outburst already on the wane; shortly afterwards the last trace vanished. Its entire duration was five minutes—from 11.18 to 11.23 A.M., Greenwich time; and during those five minutes it had traversed a space estimated at 35,000 miles! No perceptible change took place in the details of the group of spots visited by this transitory conflagration, which, it was accordingly inferred, took place at a considerable height above it.[473]

Carrington's account was precisely confirmed by an observation made at Highgate. Mr. R. Hodgson described the appearance seen by him as that "of a very brilliant star of light, much brighter than the sun's surface, most dazzling to the protected eye, illuminating the upper edges of the adjacent spots and streaks, not unlike in effect the edging of the clouds at sunset."[474]

This unique phenomenon seemed as if specially designed to accentuate the inference of a sympathetic relation between the earth and the sun. From the 28th of August to the 4th of September, 1859, a magnetic storm of unparalleled intensity, extent, and duration, was in progress over the entire globe. Telegraphic communication was everywhere interrupted—except, indeed, that it was, in some cases, found practicable to work the lines *without batteries*, by the agency of the earth-currents alone:[475] sparks issued from the wires; gorgeous auroræ draped the skies in solemn crimson over both hemispheres, and even within the tropics; the magnetic needle lost all trace of continuity in its movements, and darted to and fro as if stricken with inexplicable panic. The coincidence was drawn even closer. *At the very instant*[476] of the solar outburst witnessed by Carrington and Hodgson, the photographic apparatus at Kew registered a marked disturbance of all the three magnetic elements; while, shortly after the ensuing midnight, the electric agitation culminated, thrilling the earth with subtle vibrations, and lighting up the atmosphere from pole to pole with the coruscating splendours which, perhaps, dimly recall the times when our ancient planet itself shone as a star.

Here then, at least, the sun was—in Professor Balfour Stewart's phrase—"taken in the act"[477] of stirring up terrestrial commotions. Nor have instances since been wanting of an indubitable connection between outbreaks of individual spots and magnetic disturbances. Four such were registered in 1882; and symptoms of the same kind, including the beautiful "Rose Aurora," marked the progress across the sun of the enormous spot-group of February, 1892—the largest ever recorded at Greenwich. This extraordinary formation, which covered about 1/300 of the sun's disc, survived through five complete rotations.[478] It was remarkable for a persistent drift in latitude, its place altering progressively from 17° to 30° south of the solar equator.

Again, the central passage of an enormous spot on September 9, 1898, synchronised with a sharp magnetic disturbance and brilliant aurora;[479] and the coincidence was substantially repeated in March, 1899,[480] when it was emphasised by the prevalent cosmic calm. The theory of the connection is indeed far from clear. Lord Kelvin, in 1892, [481] pronounced against the possibility of any direct magnetic action by the sun upon the earth, on the ground of its involving an extravagant output of energy; but the fact is unquestionable that—in Professor Bigelow's words—"abnormal agitations affect the sun and the earth as a whole and at the same time."[482]

The nearer approach to the event of September 1, 1859, was photographically observed by Professor George E. Hale at Chicago, July 15, 1892.[483] An active spot in the southern hemisphere was the scene of this curiously sudden manifestation. During an interval of 12m. between two successive exposures, a bridge of dazzling light was found to have spanned the boundary-line dividing the twin-nuclei of the spot; and these, after another 27m., were themselves almost obliterated by an overflow of far-spreading brilliancy. Yet two hours later, no trace of the outburst remained, the spot and its attendant faculæ remaining just as they had been previously to its occurrence. Unlike that seen by Carrington, it was accompanied by no exceptional magnetic phenomena, although a "storm" set in next day.[484] Possibly a terrestrial analogue to the former might be discovered in the "auroral beam" which traversed the heavens during a vivid display of polar lights, November 17, 1882, and shared, there is every reason to believe, their electrical origin and character.[485]

Meantime M. Rudolf Wolf, transferred to the direction of the Zürich Observatory, where he died, December 6, 1893, had relaxed none of his zeal in the investigation of sun-spot periodicity. A laborious revision of the entire subject with the aid of fresh materials led him, in 1859,[486] to the conclusion that while the *mean* period differed little from that arrived at in 1852 of 11.11 years, very considerable fluctuations on either side of that mean were rather the rule than the exception. Indeed, the phrase "sun-spot period" must be understood as fitting very loosely the great fact it is taken to represent; so loosely, that the interval between two maxima may rise to sixteen and a half or sink below seven and a half years.[487] In 1861[488] Wolf showed, and the remark was fully confirmed at Kew, that the shortest periods brought the most acute crises, and *vice versâ*; as if for each wave of disturbance a strictly equal amount of energy were available, which might spend itself lavishly and rapidly, or slowly and parsimoniously, but could in no case be exceeded. The further inclusion of recurring solar commotions within a cycle of fifty-five and a half years was simultaneously pointed out; and Hermann Fritz showed soon afterwards that the aurora borealis is subject to an identical double periodicity.[489] The same inquirer has more recently detected both for auroræ and sun-spots a "secular period" of 222 years,[490] and the Kew observations indicate for the latter, oscillations accomplished within twenty-six and twenty-four days,[491] depending, most likely, upon the rotation of the sun. This is certainly reflected in magnetic, and perhaps in auroral periodicity. The more closely, in fact, spot-fluctuations are looked into, the more complex they prove. Maxima of one order are superposed upon, or in part neutralised by, maxima of another order;[492] originating causes are masked by modifying causes; the larger waves of the commotion are indented with minor undulations, and these again crisped with tiny ripples, while the whole rises and falls with the swell of the great secular wave, scarcely perceptible in its progress because so vast in scale.

The idea that solar maculation depends in some way upon the position of the planets occurred to Galileo in 1612.[493] It has been industriously sifted by a whole bevy of modern solar physicists. Wolf in 1859[494] found reason to believe that the eleven-year curve is determined by the action of Jupiter, modified by that of Saturn, and diversified by influences proceeding from the earth and Venus. Its tempting approach to agreement with Jupiter's period of revolution round the sun, indeed, irresistibly suggested a causal connection; yet it does not seem that the most skilful "coaxing" of figures can bring about a fundamental harmony. Carrington pointed out in 1863, that while, during *eight successive periods*, from 1770 downwards, there were approximate coincidences between Jupiter's aphelion passages and sun-spot maxima, the relation had been almost exactly reversed in the two periods preceding that date;[495] and Wolf himself finally concluded that the Jovian origin must be abandoned.[496] M. Duponchel's[497] prediction, nevertheless, of an abnormal retardation of the maximum due in 1881 through certain peculiarities in the positions of Uranus and Neptune about the time it fell due, was partially verified by the event, since, after an abortive phase of agitation in April, 1882, the final outburst was postponed to January, 1894. The interval was thus 13.5 instead of 11.1 years; and it is noticeable that the delay affected chiefly the southern hemisphere. Alternations of activity in the solar hemispheres were indeed a marked feature of the maximum of 1884, which, in M. Faye's view,[498] derived thence its indecisive character, while sharp, strong crises arise with the simultaneous advance of agitation north and south of the solar equator. The curve of magnetic disturbance followed with its usual strict fidelity the anomalous fluctuations of the sun-spot curve. The ensuing minimum occurred early in 1889, and was succeeded in 1894 by a maximum slightly less feeble than its predecessor.[499]

It cannot be said that much progress has been made towards the disclosure of the cause, or causes, of the sun-spot cycle. No external influence adequate to the effect has, at any rate, yet been pointed out. Most thinkers on this difficult subject provide a quasi-explanation of the periodicity in question through certain assumed vicissitudes affecting internal processes;[500] Sir Norman Lockyer and E. von Oppolzer reach the same end by establishing self-compensatory fluctuations in the solar atmospheric circulation; Dr. Schuster resorts to changes in the electrical conductivity of space near the sun.[501] In all these theories, however, the course of transition is arbitrarily arranged to suit a period, which imposes itself as a fact peremptorily claiming admittance, while obstinately defying explanation.

The question so much discussed, as to the influence of sun-spots on weather, does not admit of a satisfactory answer. The facts of meteorology are too complex for easy or certain classification. Effects owning dependence on one cause often wear the livery of another; the meaning of observed particulars may be inverted by situation; and yet it is only by the collection and collocation of particulars that we can hope to reach any general law. There is, however, a good deal of evidence to support the opinion—the grounds for which were primarily derived from the labours of Dr. Meldrum at Mauritius—that increased rainfall and atmospheric agitation attend spot-maxima; while Herschel's conjecture of a more copious emission of light and heat about the same epochs has recently obtained some countenance from Savélieff's measures showing a gain in the strength of the sun's radiation *pari passu* with increase in the number of spots visible on his surface.[502]

The examination of what we may call the *texture* of the sun's surface derived new interest from a remarkable announcement made by Mr. James Nasmyth in 1862.[503] He had made (as he supposed) the discovery that the entire luminous stratum of the sun is composed of a multitude of elongated shining objects on a darker background, shaped much like willow-leaves, of vast size, crossing each other in all possible directions, and possessed of unceasing relative motions. A lively controversy ensued. In England and abroad the most powerful telescopes were directed to a scrutiny encompassed with varied difficulties. Mr. Dawes was especially emphatic in declaring that Nasmyth's "willow-leaves" were nothing more than the "nodules" of Sir William Herschel seen under a misleading aspect of uniformity; and there is little doubt that he was right. It is, nevertheless, admitted that something of the kind may be seen in the penumbræ and "bridges" of spots, presenting an appearance compared by Dawes himself in 1852 to that of a piece of coarse straw-thatching left untrimmed at the edges.[504]

The term "granulated," suggested by Dawes in 1864,[505] best describes the mottled aspect of the solar disc as shown by modern telescopes and cameras. The grains, or rather the "floccules," with which it is thickly strewn, have been resolved by Langley, under exceptionally favourable conditions, into "granules" not above 100 miles in diameter; and from these relatively minute elements, composing, jointly, about one-fifth of the visible photosphere,[506] he estimates that three-quarters of the entire light of the sun are derived.[507] Janssen agrees, so far as to say that if the whole surface were as bright as its brightest parts, its luminous emission would be ten to twenty times greater than it actually is.[508]

The rapid changes in the forms of these solar cloud-summits are beautifully shown in the marvellous photographs taken by Janssen at Meudon, with exposures reduced at times to 1/100000 of a second! By their means, also, the curious phenomenon known as the *réseau photosphérique* has been made evident.[509] This consists in the diffusion over the entire disc of fleeting blurred patches, separated by a reticulation of sharply-outlined and regularly-arranged granules. The imperfect definition in the smudged areas may be due to agitations in the solar or terrestrial atmosphere, unless it be—as Dr. Schemer thinks possible[510]—merely a photographic effect. M. Janssen considers that the photospheric cloudlets change their shape and character with the progress of the sun-spot period;[511] but this is as yet uncertain.

The "grains," or more brilliant parts of the photosphere, are now generally held to represent the upper termination of ascending and condensing currents, while the darker interstices (Herschel's "pores") mark the positions of descending cooler ones. In the penumbræ of spots, the glowing streams rushing up from the tremendous sub-solar furnace are bent sideways by the powerful indraught, so as to change their vertical for a nearly horizontal motion, and are thus taken, as it were, in flank by the eye, instead of being seen end-on in mamelon-form. This gives a plausible explanation of the channelled structure of penumbræ which suggested the comparison to a rude thatch. Accepting this theory as in the main correct, we perceive that the very same circulatory process which, in its spasms of activity, gives rise to spots, produces in its regular course the singular "marbled" appearance, for the recording of which we are no longer at the mercy of the fugitive or delusive impressions of the human retina. And precisely this circulatory process it is which gives to our great luminary its permance as a *sun*, or warming and illuminating body.

FOOTNOTES:

[405] *Mem. R. A. S.*, vol. xxi., p. 157.

[406] *Ibid.*, p. 160.

[407] *Month. Not.*, vol. xxi., p. 144.

[408] *Le Soleil*, t. i., pp. 87-90 (2nd ed., 1871).

[409] See *ante*, p. 58.

[410] *Observations at Redhill (1863)*, Introduction.

[411] *Month. Not.*, vol. xxxvi., p. 142.

[412] *Cape Observations*, p. 435, *note*.

[413] *Month. Not.*, vol. x., p. 158.

[414] *Rosa Ursina*, lib. iii., p. 348.

[415] *Observations at Redhill*, p. 8.

[416] *Op.*, t. iii., p. 402.

[417] *Rosa Ursina*, lib. iv., p. 601. Both Galileo and Scheiner spoke of the *apparent* or "synodical" period, which is about one and a third days longer than the *true* or "sidereal" one. The difference is caused by the revolution of the earth in its orbit in the same direction with the sun's rotation on its axis.

[418] *Rosa Ursina*, lib. iii., p. 260.

[419] Faye, *Comptes Rendus*, t. lx., p. 818.

[420] *Ibid.*, t. xii., p. 648.

[421] *Proc. Am. Ass. Adv. of Science*, 1885, p. 85.

[422] *Observations at Redhill*, p. 221.

[423] *Am. Jour. of Science*, vol. xi., p. 169.

[424] *Month. Not.*, vol. xix., p. 1.

[425] *Vierteljahrsschrift der Naturfors. Gesellschaft* (Zürich), 1859, p. 252.

[426] Lockyer, *Chemistry of the Sun*, p. 428.

[427] Maunder, *Knowledge*, vol. xv., p. 130.

[428] *Month. Mon.*, vol. l., p. 251.

[429] Maunder, *Knowledge*, vol. xvii., p. 173.

[430] *Astr. Nach.*, No. 1,315.

[431] As late as 1866 an elaborate treatise in its support was written by F. Coyteux, entitled *Qu'est-ce que le Soleil? Peut-il être habité?* and answering the question in the affirmative.

[432] The subsequent researches of Plücker, Frankland, Wüllner, and others, showed that gases strongly compressed give an absolutely unbroken spectrum.

[433] *Comptes Rendus*, t. lx., pp. 89, 138.

[434] *Ibid.*, t. c., p. 595.

[435] *Bull. Meteor. dell Osservatorio dell Coll. Rom.*, Jan. 1, 1864, p. 4.

[436] *Quart. Jour. of Science*, vol. i., p. 222.

[437] *Ann. de Chim. et de Phys.*, t. xxii., p. 127.

[438] *Phil. Trans.*, vol. clix., p. 575.

[439] *Les Mondes*, Dec. 22, 1864, p. 707.

[440] *Comptes Rendus*, t. lx., p. 147.

[441] *Proc. Roy. Society*, vol. xvi., p. 29.

[442] *Recherches sur le Spectre Solaire*, p. 38.

[443] *Am. Jour. of Science*, 1881, vol. xxi., p. 41. Hastings stipulated only for some member of the triad, carbon, silicon, and boron.

[444] Ranyard, *Knowledge*, vol. xvi., p. 190.

[445] Young, *The Sun*, p. 337, ed. 1897.

[446] H. Draper, *Quart. Journ. of Sc.*, vol. i., p. 381; also *Phil. Mag.*, vol. xvii., 1840, p. 222.

[447] Reproduced in Arago's *Popular Astronomy*, plate xii., vol. 1.

[448] *Report Brit. Ass.*, 1859, p. 148.

[449] *Phil. Trans.*, vol. clii., p. 407.

[450] *Researches in Solar Physics*, part i., p. 20.

[451] Both the phrase and the method were suggested by Faye, who estimated the average depth of the luminous sheath of spots at 2,160 miles. *Comptes Rendus*, t. lxi., p. 1082; t. xcvi., p. 356.

[452] *Month. Not.*, vol. lv., p. 74.

[453] Sidgreaves, *Ibid.*, p. 282; Cortie, *Ibid.*, vol. lviii., p. 91.

[454] Explained by East as refraction-effects. *Jour. Brit. Astr. Ass.*, vol. viii., p. 187.

[455] *Proc. Roy. Soc.*, vol. xiv., p. 39.

[456] *Potsdam Publicationen*, No. 18; *Astr. Nach.*, Nos. 3,000, 3,287.

[457] Faye, *Comptes Rendus*, t. cxi., p. 77; Bélopolsky, *Astr. Nach.*, No. 2,991.

[458] *Ibid.*, Nos. 3,275, 3,344.

[459] Lockyer, *Contributions to Solar Physics*, p. 70.

[460] *Le Soleil*, p. 87.

[461] *Proc. Roy. Soc.*, vol. xv., p. 256.

[462] *Phil. Mag.*, vol. xvi., p. 460.

[463] *Recherches sur la Rotation du Soleil*, p. 12.

[464] Hale, *Astr. and Astrophysics*, vol. xi., p. 814.

[465] *Jour. Brit. Astr. Ass.*, vol. i., p. 177.

[466] *Comptes Rendus*, t. lxxv., p. 1664; *Revue Scientifique*, t. v., p. 359 (1883). Mr. Herbert Spencer had already (in *The Reader*, Feb. 25, 1865) put forward an opinion that spots were of the nature of “cyclonic clouds.”

[467] *The Sun*, p. 174. For Faye’s answer to the objection, see *Comptes Rendus*, t. xcv., p. 1310.

[468] A revised edition appeared in 1897.

[469] *Astr. and Astrophysics*, vol. xii., p. 832.

[470] *Proc. Roy. Soc.*, No. 244.

[471] *Astr. Nach.*, No. 3,146; *Astr. and Astrophysics*, vol. xii., pp. 419, 736.

[472] *Sirius*, Sept., 1893; *ibid.*, vol. xxiii., p. 97; *Astrophy. Jour.*, vol. i., p. 112 (Wilczynski), p. 178 (Keeler); vol. ii., p. 73 (Hale).

[473] *Month. Not.*, vol. xx., p. 13.

[474] *Ibid.*, p. 15.

[475] *Am. Jour.*, vol. xxix. (2nd series), pp. 94, 95.

[476] The magnetic disturbance took place at 11.15 A.M., three minutes before the solar blaze compelled the attention of Carrington.

[477] *Phil. Trans.*, vol. cli., p. 428.

[478] Maunder, *Journal Brit. Astr. Ass.*, vol. ii., p. 386; Miss E. Brown, *Ibid.*, p. 210; Month. Not., vol. lii., p. 354.

[479] *Observatory*, vol. xxi., p. 387; Maunder, *Knowledge*, vol. xxi., p. 228; Fényi, *Astroph. Jour.*, vol. x., p. 333.

[480] *Ibid.*, p. 336; W. Anderson, Observatory, vol. xxii., p. 196.

[481] *Proc. Roy. Society*, vol. lii., p. 307; Rev. W. Sidgreaves, *Mem. R. A. S.*, vol. liv., p. 85.

[482] *Report on Solar and Terrestrial Magnetism*, Washington, 1898, p. 27.

[483] *Astr. and Astrophysics*, vol. xi., p. 611.

[484] *Ibid.*, p. 819 (Sidgreaves).

[485] See J. Rand Capron, *Phil. Mag.*, vol. xv., p. 318.

[486] *Mittheilungen über die Sonnenflecken*, No. ix., *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich*, Jahrgang 4.

[487] *Mitth.*, No. lii., p. 58 (1881).

[488] *Ibid.*, No. xii., p. 192. Baxendell, of Manchester, reached independently a similar conclusion. See *Month. Not.*, vol. xxi., p. 141.

[489] Wolf, *Mitth.*, No. xv., p. 107, etc. Olmsted, following Hansteen, had already, in 1856, sought to establish an auroral period of sixty-five years. *Smithsonian Contributions*, vol. viii., p. 37.

[490] Hahn, *Ueber die Reziehungen der Sonnenfleckenperiode zu meteorologischen Erscheinungen*, p. 99 (1877).

[491] *Report Brit. Ass.*, 1881, p. 518; 1883, p. 418.

[492] The Rev. A. Cortie (*Month. Not.*, vol. lx., p. 538) detects the influence of a short subsidiary cycle, Dr. W. J. S. Lockyer that of a thirty-five year period (*Nature*, June 20, 1901). Professor Newcomb (*Astroph. Jour.*, vol. xiii., p. 11) considers that solar activity oscillates uniformly in 11.13 years, with superposed periodic variations.

[493] *Opere*, t. iii., p. 412.

[494] *Mitth.*, Nos. vii. and xviii.

[495] *Observations at Redhill*, p. 248.

[496] *Comptes Rendus*, t. xcv., p. 1249.

[497] *Ibid.*, t. xciii., p. 827; t. xcvi., p. 1418.

[498] *Ibid.*, t. c, p. 593.

[499] Ellis, *Proc. Roy. Society*, vol. lxiii., p. 70.

[500] Schultz, *Astr. Nach.*, Nos. 2,817-18, 2,847-8; Wilsing, *Ibid.*, No. 3,039; Bélopolsky, *Ibid.*, No. 2,722.

[501] *Report Brit. Ass.*, 1892, p. 635.

[502] A. W. Augur, *Astroph. Jour.*, vol. xiii., p. 346.

[503] *Report Brit. Ass.*, 1862, p. 16 (pt. ii.).

[504] *Mem. R. A. S.*, vol. xxi., p. 161.

[505] *Month. Not.*, vol. xxiv., p. 162.

[506] *Am. Jour. of Science*, vol. vii., 1874, p. 92.

[507] Young, *The Sun*, p. 103.

[508] *Ann. Bur. Long.*, 1879, p. 679.

[509] *Ibid.*, 1878, p. 689.

[510] *Himmelsphotographie*, p. 273.

[511] Ranyard, *Knowledge*, vols. xiv., p. 14, xvi., p. 189; see also the accompanying photographs.

CHAPTER III

RECENT SOLAR ECLIPSES

By observations made during a series of five remarkable eclipses, comprised within a period of eleven years, knowledge of the solar surroundings was advanced nearly to its present stage. Each of these events brought with it a fresh disclosure of a definite and unmistakable character. We will now briefly review this orderly sequence of discovery.

Photography was first systematically applied to solve the problems presented by the eclipsed sun, July 18, 1860. It is true that a daguerreotype,[512] taken by Berkowski with the Königsberg heliometer during the eclipse of 1851, is still valuable as a record of the corona of that year; and some subsequent attempts were made to register partial phases of solar occultation, notably by Professor Bartlett at West Point in 1854;[513] but the ground remained practically unbroken until 1860.

In that year the track of totality crossed Spain, and thither, accordingly, Warren de la Rue transported his photo-heliograph, and Father Secchi his six-inch Cauchoix refractor. The question then primarily at issue was that relating to the nature of the red protuberances. Although, as already stated, the evidence collected in 1851 gave a reasonable certainty of their connection with the sun, objectors were not silenced; and when the side of incredulity was supported by so considerable an authority as M. Faye, it was impossible to treat it with contempt. Two crucial tests were available. If it could be shown that the fantastic shapes suspended above the edge of the dark moon were seen under an identical aspect from two distant stations, that fact alone would annihilate the theory of optical illusion or “mirage”; while the certainty that they were progressively concealed by the advancing moon on one side, and uncovered on the other, would effectually detach them from dependence on our satellite, and establish them as solar appendages.

Now both these tests were eminently capable of being applied by photography. But the difficulty arose that nothing was known as to the chemical power of the rosy prominence-light, while everything depended on its right estimation. A shot had to be fired, as it were, in the dark. It was a matter of some surprise, and of no small congratulation, that, in both cases, the shot took effect.

De la Rue occupied a station at Rivabellosa, in the Upper Ebro valley; Secchi set up his instrument at Desierto de las Palmas, about 250 miles to the south-east, overlooking the Mediterranean. From the totally eclipsed sun, with its strange garland of flames, each observer derived several perfectly successful impressions, which were found, on comparison, to agree in the most minute details. This at once settled the fundamental question as to the substantial reality of these objects; while their solar character was demonstrated by the passage of the moon *in front* of them, indisputably attested by pictures taken at successive stages of the eclipse. That forms seeming to defy all laws of equilibrium were, nevertheless, not wholly evanescent, appeared from their identity at an interval of seven minutes, during which the lunar shadow was in transit from one station to the other; and the singular energy of their actinic rays was shown by the record on the sensitive plates of some prominences invisible in the telescope. Moreover, photographic evidence strongly confirmed the inference—previously drawn by Grant and others, and now with fuller assurance by Secchi—that an uninterrupted stratum of prominence-matter encompasses the sun on all sides, forming a reservoir from which gigantic jets issue, and into which they subside.

Thus, first-fruits of accurate knowledge regarding the solar surroundings were gathered, while the value of the brief moments of eclipse gained indefinite increase, by supplementing transient visual impressions with the faithful and lasting records of the camera.

In the year 1868 the history of eclipse spectroscopy virtually began, as that of eclipse photography in 1860; that is to say, the respective methods then first gave definite results. On the 18th of August, 1868, the Indian and Malayan peninsulas were traversed by a lunar shadow producing total obscuration during five minutes and thirty-eight seconds. Two English and two French expeditions were despatched to the distant regions favoured by an event so propitious to the advance of knowledge, chiefly to obtain the verdict of the prism as to the composition of prominences. Nor were they despatched in vain. An identical discovery was made by nearly all the observers. At Jamkandi, in the Western Ghauts, where Lieutenant (now Colonel) Herschel was posted, unremitting bad weather threatened to baffle his eager expectations; but during the lapse of the critical five and a half minutes the clouds broke, and across the driving wrack a “long, finger-like projection” jutted out over the margin of the dark lunar globe. In another moment the spectroscope was pointed towards it; three bright lines—red, orange, and blue—flashed out, and the problem was solved.[514] The problem was solved in this general sense, that the composition out of glowing vapours of the objects infelicitously termed “protuberances” or “prominences” was no longer doubtful; although further inquiry was needed for the determination of the particular species to which those vapours belonged.

Similar, but more complete observations were made, with less atmospheric hindrance, by Tennant and Janssen at Guntoor, by Pogson at Masulipatam, and by Rayet at Wha-Tonne, on the coast of the Malay peninsula, the last observer counting as many as nine bright lines.[515] Among them it was not difficult to recognise the characteristic light of hydrogen; and it was generally, though over-hastily, assumed that the orange ray matched the luminous emissions of sodium. But fuller opportunities were at hand.

The eclipse of 1868 is chiefly memorable for having taught astronomers to do without eclipses, so far, at least, as one particular branch of solar inquiry is concerned. Inspired by the beauty and brilliancy of the variously tinted prominence-lines revealed to him by the spectroscope, Janssen exclaimed to those about him, “Je verrai ces lignes-là en dehors des éclipses!” On the following morning he carried into execution the plan which formed itself in his brain while the phenomenon which suggested it was still before his eyes. It rests upon an easily intelligible principle.

The glare of our own atmosphere alone hides the appendages of the sun from our daily view. To a spectator on an airless planet, the central globe would appear attended by all its splendid retinue of crimson prominences, silvery corona, and far-spreading zodiacal light projected on the star-spangled black background of an absolutely unilluminated sky. Now the spectroscope offers the means of indefinitely weakening atmospheric glare by diffusing a constant amount of it over an area widened *ad libitum*. But monochromatic or “bright-line” light is, by its nature, incapable of being so diffused. It can, of course, be *deviated* by refraction to any extent desired; but it always remains equally concentrated, in whatever direction it may be thrown. Hence, when it is mixed up with continuous light—as in the case of the solar flames shining through our atmosphere—it derives a *relative* gain in intensity from every addition to the dispersive power of the spectroscope with which the heterogeneous mass of beams is analysed. Employ prisms enough, and eventually the undiminished rays of persistent colour will stand out from the continually fading rainbow-tinted band, by which they were at first effectually veiled.

This Janssen saw by a flash of intuition while the eclipse was in progress; and this he realised at 10 A.M. next morning, August 19, 1868—the date of the beginning of spectroscopic work at the margin of the unobscured sun. During the whole of that day and many subsequent ones, he enjoyed, as he said, the advantage of a prolonged eclipse. The intense interest with which he surveyed the region suddenly laid bare to his scrutiny was heightened by evidences of rapid and violent change. On the 18th of August, during the eclipse, a vast spiral structure, *at least* 89,000 miles high, was perceived, planted in surprising splendour on the rim of the interposed moon. If was formed as General Tennant judged from its appearance in his photographs, by the encounter of two mounting torrents of flame, and was distinguished as the “Great Horn.” Next day it was in ruins; hardly a trace remained to show where it had been.[516] Janssen’s spectroscope furnished him besides with the strongest confirmation of what had already been reported by the telescope and the camera as to the continuous nature of the scarlet “sierra” lying at the base of the prominences. Everywhere at the sun’s edge the same bright lines appeared.

It was not until the 19th of September that Janssen thought fit to send news of his discovery to Europe. It seemed little likely to be anticipated; yet a few minutes before his despatch was handed to the Secretary of the Paris Academy of Sciences, a communication similar in purport had been received from Sir Norman Lockyer. There is no need to discuss the narrow and wearisome question of priority; each of the competitors deserves, and has obtained, full credit for his invention. With noteworthy and confident prescience, Lockyer, in 1866, before anything was yet known regarding the constitution of the “red flames,” ordered a strongly dispersive spectroscope for the express purpose of viewing, apart from eclipses, the bright-line spectrum which he expected them to give. Various delays, however, supervened, and the instrument was not in his hands until October 16, 1868. On the 20th he picked up the vivid rays, of which the presence and (approximately) the positions had in the interim become known. But there is little doubt that, even without that previous knowledge, they would have been found; and that the eclipse of August 18 only accelerated a discovery already assured.

Sir William Huggins, meanwhile, had been tending towards the same goal during two and a half years in his observatory at Tulse Hill. The principle of the spectroscopic visibility of prominence-lines at the edge of an uneclipsed sun was quite explicitly stated by him in February, 1868,[517] and he devised various apparatus for bringing them into actual view; but not until he knew where to look did he succeed in seeing them.

Astronomers, thus liberated, by the acquisition of power to survey them at any time, from the necessity of studying prominences during eclipses, were able to concentrate the whole of their attention on the corona. The first thing to be done was to ascertain the character of its spectrum. This was seen in 1868 only as a faintly continuous one; for Rayet, who seems to have perceived its distinctive bright line far above the summits of the flames, connected it, nevertheless, with those objects. On the other hand, Lieutenant Campbell ascertained on the same occasion the polarisation of the coronal light in planes passing through the sun's centre,[518] thereby showing that light to be, in whole or in part, reflected sunshine. But if reflected sunshine, it was objected, the chief at least of the dark Fraunhofer lines should be visible in it, as they are visible in moonbeams, sky illumination, and all other sun-derived light. The objection was well founded, but was prematurely urged, as we shall see.

On the 7th of August, 1869, a track of total eclipse crossed the continent of North America diagonally, entering at Behring's Straits, and issuing on the coast of North Carolina. It was beset with observers; but the most effective work was done in Iowa. At Des Moines, Professor Harkness of the Naval Observatory, Washington, obtained from the corona an "absolutely continuous spectrum," slightly less bright than that of the full moon, but traversed by a single green ray.[519] The same green ray was seen at Burlington and its position measured by Professor Young of Dartmouth College.[520] It appeared to coincide with that of a dark line of iron in the solar spectrum, numbered 1,474 on Kirchhoff's scale. But in 1876 Young was able, by the use of greatly increased dispersion, to resolve the Fraunhofer line "1474′ into a pair, the more refrangible member of which he considered to be the reversal of the green coronal ray.[521] Scarcely called in question for over twenty years, the identification nevertheless broke down through the testimony of the eclipse-photographs of 1898. Sir Norman Lockyer derived from them a position for the line in question notably higher up in the spectrum than that previously assigned to it. Instead of 5,317, its true wave-length proved to be 5,303 ten millionths of a millimetre;[522] nor does it make any show by absorption in dispersed sunlight. The originating substance, designated “coronium,” of which nothing is known to terrestrial chemistry, continues luminous[523] at least 300,000 miles above the sun’s surface, and is hence presumably much lighter even than hydrogen.

A further trophy was carried off by American skill[524] sixteen months after the determination due to it of the distinctive spectrum of the corona. The eclipse of December 22, 1870, though lasting only two minutes and ten seconds, drew observers from the New, as well as from the Old World to the shores of the Mediterranean. Janssen issued from beleaguered Paris in a balloon, carrying with him the *vital parts* of a reflector specially constructed to collect evidence about the corona. But he reached Oran only to find himself shut behind a cloud-curtain more impervious than the Prussian lines. Everywhere the sky was more or less overcast. Lockyer’s journey from England to Sicily, and shipwreck in the *Psyche*, were recompensed with a glimpse of the solar aureola during *one second and a half*! Three parties stationed at various heights on Mount Etna saw absolutely nothing. Nevertheless important information was snatched in despite of the elements.

The prominent event was Young’s discovery of the “reversing layer.” As the surviving solar crescent narrowed before the encroaching moon, “the dark lines of the spectrum,” he tells us, “and the spectrum itself, gradually faded away, until all at once, as suddenly as a bursting rocket shoots out its stars, the whole field of view was filled with bright lines more numerous than one could count. The phenomenon was so sudden, so unexpected, and so wonderfully beautiful, as to force an involuntary exclamation.”[525] Its duration was about two seconds, and the impression produced was that of a complete reversal of the Fraunhofer spectrum—that is, the substitution of a bright for every dark line.

Now something of the kind was theoretically necessary to account for the dusky rays in sunlight which have taught us so much, and have yet much more to teach us; so that, although surprising from its transitory splendour, the appearance could not strictly be called “unexpected.” Moreover, its premonitory symptom in the fading out of these rays had been actually described by Secchi in 1868,[526] and looked for by Young as the moon covered the sun in August 1869. But with the slit of his spectroscope placed *normally* to the sun’s limb, the bright lines gave a flash too thin to catch the eye. In 1870 the position of the slit was *tangential*—it ran along the shallow bed of incandescent vapours, instead of cutting across it: hence his success.

The same observation was made at Xerez de la Frontera by Mr. Pye, a member of Young’s party; and, although an exceedingly delicate one, has since frequently been repeated. The whole Fraunhofer series appeared bright (omitting other instances) to Maclear, Herschel, and Fyers in 1871, at the beginning or end of totality; to Pogson, at the break-up of an annual eclipse, June 6, 1872; to Stone at Klipfontein, April 16, 1874, when he saw “the field full of bright lines.”[527] But between the picture presented by the “véritable pluie de lignes brilliantes,”[528] which descended into M. Trépied’s spectroscope for three seconds after the disappearance of the sun, May 17, 1882, and the familiar one of the dark-line solar spectrum, certain differences were perceiving, showing their relation to be not simply that of a positive to a negative impression.

A “reversing layer,” or stratum of mixed vapours, glowing, but at a lower temperature than that of the actual solar surface, was an integral part of Kirchhoff’s theory of the production of the Fraunhofer lines. Here it was assumed that the missing rays were stopped, and here also it was assumed that the missing rays would be seen bright, could they be isolated from the overpowering splendour of their background. This isolation is effected by eclipses, with the result—beautifully confirmatory of theory—of *reversing*, or turning from dark to bright, the Fraunhofer spectrum. The completeness and precision of the reversal, however, could not be visually attested; and a quarter of a century elapsed before a successful “snap-shot” provided photographic evidence on the subject. It was taken at Novaya Zemlya by Mr. Shackleton, a member of the late Sir George Baden-Powell’s expedition to observe the eclipse of August 9, 1896;[529] and similar records in abundance were secured during the Indian eclipse of January 22, 1898,[530] and the Spanish-American eclipse of May 28, 1900.[531] The result of their leisurely examination has been to verify the existence of a “reversing-layer,” in the literal sense of the term. It is true that no single “flash” photograph is an inverted transcript of the Fraunhofer spectrum. The lines are, indeed, in each case—speaking broadly—the same; but their relative intensities are widely different. Yet this need occasion no surprise when we remember that the Fraunhofer spectrum integrates the absorption of multitudinous strata, various in density and composition, while only the upper section of the formation comes within view of the sensitive plates exposed at totalities, the low-lying vaporous beds being necessarily covered by the moon. The total depth of this glowing envelope may be estimated at 500 to 600 miles, and its normal state seems to be one of profound tranquillity, judging from the imperturbable aspect of the array of dark lines due to its sifting action upon light.

The last of the five eclipses which we have grouped together for separate consideration was visible in Southern India and Australia, December 12, 1871. Some splendid photographs were secured by the English parties on the Malabar coast, showing, for the first time, the remarkable branching forms of the coronal emanations; but the most conspicuous result was Janssen’s detection of some of the dark Fraunhofer lines, long vainly sought in the continuous spectrum of the corona. Chief among these was the D-line of sodium, the original index, it might be said, to solar chemistry. No proof could be afforded more decisive that this faint *echoing back* of the distinctive notes of the Fraunhofer spectrum, that the polariscope had spoken the truth in asserting a large part of the coronal radiance to be reflected sunlight. But it is usually so drenched in original luminosity, that its special features are almost obliterated. Janssen’s success in seizing them was due in part to the extreme purity of the air at Sholoor, in the Neilgherries, where he was stationed; in part to the use of an instrument adapted by its large aperture and short focus to give an image of the utmost brilliancy. His observation, repeated during the Caroline Island eclipse of 1883, was photographically verified ten years later by M. de la

Baume Pluvinel in Senegal.[532]

An instrument of great value for particular purposes was introduced into eclipse-work in 1871. The "slitless spectroscope" consists simply of a prism placed outside the object-glass of a telescope or the lens of a camera, whereby the radiance encompassing the eclipsed sun is separated into as many differently tinted rings as it contains different kinds of light. These tinted rings were simultaneously viewed by Respighi at Poodacottah, and by Lockyer at Baikul. Their photographic registration by the latter in 1875 initiated the transformation of the slitless spectroscope into the prismatic camera.[533] Meanwhile, the use of an ordinary spectroscope by Herschel and Tennant at Dodabetta showed the green ray of coronium to be just as bright in a rift as in the adjacent streamer. The visible structure of the corona was thus seen to be independent of the distribution of the gases which enter into its composition.

By means, then, of the five great eclipses of 1860-71 it was ascertained: first, that the prominences, and at least the lower part of the corona, are genuine solar appurtenances; secondly, that the prominences are composed of hydrogen and other gases in a state of incandescence, and rise, as irregular outliers, from a continuous envelope of the same materials, some thousands of miles in thickness; thirdly, that the corona is of a highly complex constitution, being made up in part of glowing vapours, in part of matter capable of reflecting sunlight. We may now proceed to consider the results of subsequent eclipses.

These have raised, and have helped to solve, some very curious questions. Indeed, every carefully watched total eclipse of the sun stimulates as well as appeases curiosity, and leaves a legacy of outstanding doubt, continually, as time and inquiry go on, removed, but continually replaced. It cannot be denied that the corona is a perplexing phenomenon, and that it does not become less perplexing as we know more about it. It presented itself under quite a new and strange aspect on the occasion of the eclipse which visited the Western States of North America, July 29, 1878. The conditions of observation were peculiarly favourable. The weather was superb; above the Rocky Mountains the sky was of such purity as to permit the detection of Jupiter's satellites with the naked eye on several successive nights. The opportunity for advancing knowledge was made the most of. Nearly a hundred astronomers, including several Englishmen, occupied twelve separate posts, and prepared for an attack in force.

The question had often suggested itself, and was a natural one to ask, whether the corona sympathises with the general condition of the sun? whether, either in shape or brilliancy, it varies with the progress of the sun-spot period? A more propitious moment for getting this question answered could hardly have been chosen than that at which the eclipse occurred. Solar disturbance was just then at its lowest ebb. The development of spots for the month of July, 1878, was represented on Wolf's system of "relative numbers" by the fraction 0·1, as against 135·4 for December, 1870, an epoch of maximum activity. The "chromosphere"[534] was, for the most part, shallow and quiescent; its depth, above the spot zones, had sunk from about 6,000 to 2,000 miles;[535] prominences were few and faint. Obviously, if a type of corona corresponding to a minimum of sun-spots existed, it should be seen then or never. It *was* seen; but while, in some respects, it agreed with anticipation, in others it completely set it at naught.

The corona of 1878, as compared with those of 1869, 1870, and 1871, was generally admitted to be shrunken in its main outlines and much reduced in brilliancy. Lockyer pronounced it ten times fainter than in 1871; Harkness estimated its light at less than one-seventh that derived from the mist-blotted aureola of 1870.[536] In shape, too, it was markedly different. When sun-spots are numerous, the corona appears to be most fully developed above the spot-zones, thus offering to our eyes a rudely quadrilateral contour. The four great luminous sheaves forming the corners of the square are made up of rays curving together from each side into "synclinal" or ogival groups, each of which may be compared to the petal of a flower. To Janssen, in 1871, the eclipsing moon seemed like the dark heart of a gigantic dahlia, painted in light on the sky; and the similitude to the ornament on a compass-card, used by Airy in 1851, well conveys the decorative effect of the beamy, radiated kind of aureola, never, it would appear, absent when solar activity is at a tolerably high pitch. In his splendid volume on eclipses,[537] with which the systematic study of coronal structure may be said to have begun, Mr. Ranyard first generalised the synclinal peculiarity by a comparison of records; but the symmetry of the arrangement, though frequently striking, is liable to be confused by secondary formations. He further pointed out, with the help of careful drawings from the photographs of 1871 made by Mr. Wesley, the curved and branching shapes assumed by the component filaments of massive bundles of rays. Nothing of all this, however, was visible in 1878. Instead, there was seen, as the groundwork of the corona, a ring of pearly light, nebulous to the eye, but shown by telescopes and in photographs to have a fibrous texture, as if made up of tufts of fine hairs. North and south, a series of short, vivid, electrical-looking flame-brushes diverged with conspicuous regularity from each of the solar poles. Their direction was not towards the centre of the sun, but towards each summit of his axis, so that the farther rays on either side started almost tangentially to the surface.

But the leading, and a truly amazing, characteristic of the phenomenon was formed by two vast, faintly-luminous *wings* of light, expanded on either side of the sun in the direction of the ecliptic. These were missed by very few careful onlookers; but the extent assigned to them varied with skill in, and facilities for seeing. By far the most striking observations were made by Newcomb at Separation (Wyoming), by Cleveland Abbe from the shoulder of Pike's Peak, and by Langley at its summit, an elevation of 14,100 feet above the sea. Never before had an eclipse been viewed from anything approaching that altitude, or under so translucent a sky. A proof of the great reduction in atmospheric glare was afforded by the perceptibility of the corona four minutes after totality was over. For the 165 seconds of its duration, the remarkable streamers above alluded to continued "persistently visible," stretching away right and left of the sun to a distance of at least ten million miles! One branch was traced over an apparent extent of fully twelve lunar diameters, without sign of a definite termination having been reached; and there were no grounds for supposing the other more restricted.

The resemblance to the zodiacal light was striking; and a community of origin between that enigmatical member of our system and the corona was irresistibly suggested. We should, indeed, expect to see, under such exceptionally favourable atmospheric conditions as Professor Langley enjoyed on Pike’s Peak, the *roots* of the zodiacal light presenting near the sun just such an appearance as he witnessed; but we can imagine no reason why their visibility should be associated with a low state of solar activity. Nevertheless this seems to be the case with the streamers which astonished astronomers in 1878. For in August, 1867, when similar equatorial emanations, accompanied by similar symptoms of polar excitement, were described and depicted by Grosch[538] of the Santiago Observatory, sun-spots were at a minimum; while the corona of 1715, which appears from the record of it by Roger Cotes[539] to have been of the same type, preceded by three years the ensuing maximum. The eclipsed sun was seen by him at Cambridge, May 2, 1715, encompassed with a ring of light about one-sixth of the moon’s diameter in breadth, upon which was superposed a luminous cross formed of long bright branches lying very nearly in the plane of the ecliptic, and shorter polar arms so faint as to be only intermittently visible. The resemblance between his sketch and Cleveland Abbe’s drawing of the corona of 1878 is extremely striking. It should, nevertheless, be noted that some conspicuous spots were visible on the sun’s disc at the time of Cotes’s eclipse, and that the preceding minimum (according to Wolf) occurred in 1712. Thus, the coincidence of epochs is imperfect.

Professor Cleveland Abbe was fully persuaded that the long rays carefully observed by him from Pike’s Peak were nothing else than streams of meteorites rushing towards or from perihelion; and it is quite certain that the solar neighbourhood must be crowded with such bodies. But the peculiar structure at the base of the streamers displayed in the photographs, the curved rays meeting in pointed arches like Gothic windows, the visible upspringing tendency, the filamentous texture,[540] speak unmistakably of the action of forces proceeding *from* the sun, not of extraneous matter circling round him.

A further proof of sympathetic change in the corona is afforded by the analysis of its light. In 1878 the bright line so conspicuous in the coronal spectrum in 1870 and 1871 had faded to the very limit of visibility. Several skilled observers failed to see it at all; but Young and Eastman succeeded in tracing the green “coronium” ray all round the sun, to a height estimated at 340,000 miles. The substance emitting it was thus present, though in a low state of incandescence. The continuous spectrum was relatively strong; faint traces of the Fraunhofer lines attested for it an origin, in part by reflection; and polarisation was undoubted, increasing towards the limb, whereas in 1870 it reached a maximum at a considerable distance from it. Experiments with Edison’s tasimeter seemed to show that the corona radiates a sensible amount of heat.

The next promising eclipse occurred May 17, 1882. The concourse of astronomers which has become usual on such occasions assembled this time at Sohag, in Upper Egypt. Rarely have seventy-four seconds been turned to such account. To each observer a special task was assigned, and the advantages of a strict division of labour were visible in the variety and amount of the information gained.

The year 1882 was one of numerous sun-spots. On the eve of the eclipse twenty-three separate maculæ were counted. If there were any truth in the theory which connected coronal forms with fluctuations in solar activity, it might be anticipated that the vast equatorial expansions and polar "brushes" of 1878 would be found replaced by the star-like structure of 1871. This expectation was literally fulfilled. No lateral streamers were to be seen. The universal failure to perceive them, after express search in a sky of the most transparent purity, justifies the emphatic assertion that *they were not there*. Instead, the type of corona observed in India eleven years earlier, was reproduced with its shining aigrettes, complex texture and brilliant radiated aspect.

Concordant testimony was given by the spectroscope. The reflected light derived from the corona was weaker than in 1878, while its original emissions were proportionately intensified. Nevertheless, most of the bright lines recorded as coronal[541] were really due, there can be no doubt, to diffused chromospheric light. On this occasion, the first successful attempt was made to photograph the coronal spectrum procured in the ordinary way with a slit and prisms, while the prismatic camera was also profitably employed. It served to bring out at least one important fact—that of the uncommon strength in chromospheric regions of the twin violet beams of calcium, designated "H" and "K"; and prominence-photography signalised its improvement by the registration, in the spectrum of one such object, of twenty-nine rays, including many of the ultra-violet hydrogen series discovered by Sir William Huggins in the emission of white stars.[542]

Dr. Schuster's photographs of the corona itself were the most extensive, as well as the most detailed, of any yet secured. One rift imprinted itself on the plates to a distance of nearly a diameter and a half from the limb; and the transparency of the streamers was shown by the delineation through them of the delicate tracery beyond. The singular and picturesque feature was added of a bright comet, self-depicted in all the exquisite grace of swift movement betrayed by the fine curve of its tail, hurrying away from one of its rare visits to our sun, and rendered momentarily visible by the withdrawal of the splendour in which it had been, and was again quickly veiled.

From a careful study of these valuable records Sir William Huggins derived the idea of a possible mode of photographing the corona *without an eclipse*.[543] As already stated, its ordinary invisibility is entirely due to the "glare" or reflected light diffused through our atmosphere. But Huggins found, on examining Schuster's negatives, that a large proportion of the light in the coronal spectrum, both continuous and interrupted, is collected in the violet region between the Fraunhofer lines G and H. There, then, he hoped that, all other rays being excluded, it might prove strong enough to vanquish inimical glare, and stamp on prepared plates, through *local* superiority in illuminative power, the forms of the appendage by which it is emitted.

His experiments were begun towards the end of May, 1882, and by September 28 he had obtained a fair earnest of success. The exclusion of all other qualities of light save that with which he desired to operate, was accomplished by using chloride of silver as his sensitive material, that substance being chemically inert to all other but those precise rays in which the corona has the advantage.[544] Plates thus sensitised received impressions which it was hardly possible to regard as spurious. “Not only the general features,” Captain Abney affirmed,[545] “are the same, but details, such as rifts and streamers, have the same position and form.” It was found, moreover, that the corona photographed during the total eclipse of May 6, 1883, was intermediate in shape between the coronas photographed by Sir William Huggins before and after that event, each picture taking its proper place in a series of progressive modifications highly interesting in themselves, and full of promise for the value of the method employed to record them.[546] But experiments on the subject were singularly interrupted. The volcanic explosion in the Straits of Sunda in August, 1883, brought to astronomers a peculiarly unwelcome addition to their difficulties. The magnificent sunglows due to the diffractive effects on light of the vapours and fine dust flung in vast volumes into the air, and rapidly diffused all round the globe, betokened an atmospheric condition of all others the most prejudicial to delicate researches in the solar vicinity. The filmy coronal forms, accordingly, which had been hopefully traced on the Tulse Hill plates ceased to appear there; nor were any substantially better results obtained by Mr. C. Ray Woods, in the purer air either of the Riffel or the Cape of Good Hope, during the three ensuing years. Moreover, attempts to obtain coronal photographs during the partial phases of the eclipse of August 29, 1886, completely failed. No part of the lunar globe became visible in relief against circumfluous solar radiance on any of the plates exposed at Grenada; and what vestiges of “structure” there were, came out almost better *upon* the moon than *beside* her, thus stamping themselves at once as of atmospheric origin.

That the effect sought is a perfectly possible one is proved by the distinct appearance of the moon projected on the corona, in photographs of the partially eclipsed sun in 1858, 1889, and 1890, and very notably in 1898 and 1900.[547]

In the spring of 1893, Professor Hale[548] attacked the problem of coronal daylight photography, employing the “double-slit” method so eminently serviceable for the delineation of prominences.[549] But neither at Kenwood nor at the summit of Pike’s Peak, whither, in the course of the summer, he removed his apparatus, was any action of the desired kind secured. Similar ill success attended his and Professor Riccò‘s employment, on Mount Etna in July, 1894, of a specially designed coronagraph. Yet discouragement did not induce despair. The end in view is indeed too important to be readily abandoned; but it can be reached only when a more particular acquaintance with the nature of coronal light than we now possess indicates the appropriate device for giving it a preferential advantage in self-portraiture. Moreover, the effectiveness of this device may not improbably be enhanced, through changes in the coronal spectrum at epochs of sun-spot maximum.

The prosperous result of the Sohag observations stimulated the desire to repeat them on the first favourable opportunity. This offered itself one year later, May 6, 1883, yet not without the drawbacks incident to terrestrial conditions. The eclipse promised was of rare length, giving no less than five minutes and twenty-three seconds of total obscurity, but its path was almost exclusively a "water-track." It touched land only on the outskirts of the Marquesas group in the Southern Pacific, and presented, as the one available foothold for observers, a coral reef named Caroline Island, seven and a half miles long by one and a half wide, unknown previously to 1874, and visited only for the sake of its stores of guano. Seldom has a more striking proof been given of the vividness of human curiosity as to the condition of the worlds outside our own, than in the assemblage of a group of distinguished men from the chief centres of civilisation, on a barren ridge, isolated in a vast and tempestuous ocean, at a distance, in many cases, of 11,000 miles and upwards from the ordinary scene of their labours. And all these sacrifices—the cost and care of preparation, the transport and readjustment of delicate instruments, the contrivance of new and more subtle means of investigating phenomena—on the precarious chance of a clear sky during one particular five minutes! The event, though fortunate, emphasised the hazard of the venture. The observation of the eclipse was made possible only by the happy accident of a serene interval between two storms.

The American expedition was led by Professor Edward S. Holden, and to it were courteously permitted to be attached Messrs. Lawrance and Woods, photographers, sent out by the Royal Society of London. M. Janssen was chief of the French Academy mission; he was accompanied from Meudon by Trouvelot, and joined from Vienna by Palisa, and from Rome by Tacchini. A large share of the work done was directed to assuring or negativing previous results. The circumstances of an eclipse favour illusion. A single observation by a single observer, made under unfamiliar conditions, and at a moment of peculiar excitement, can scarcely be regarded as offering more than a suggestion for future inquiry. But incredulity may be carried too far. Janssen, for instance, felt compelled, by the survival of unwise doubts, to devote some of the precious minutes of obscurity at Caroline Island to confirming what, in his own persuasion, needed no confirmation—that is, the presence of reflected Fraunhofer lines in the spectrum of the corona. Trouvelot and Palisa, on the other hand, instituted an exhaustive, but fruitless search for the spurious "intramercurian" planets announced by Swift and Watson in 1878.

New information, however, was not deficient. The corona proved identical in type with that of 1882,[550] agreeably to what was expected at an epoch of protracted solar activity. The characteristic aigrettes were of even greater brilliancy than in the preceding year, and the chemical effects of the coronal light proved unusually intense. Janssen's photographs, owing to the considerable apertures (six and eight inches) of his object-glasses, and the long exposures permitted by the duration of totality, were singularly perfect; they gave a greater extension to the coronal than could be traced with the telescope,[551] and showed its forms as absolutely fixed and of remarkable complexity.

The English pictures, taken with exposures up to sixty seconds, were likewise of great value. They exhibited details of structure from the limb to the tips of the streamers, which terminated definitely, and as it seemed actually, where the impressions on the plates ceased. The coronal spectrum was also successfully photographed, and although the reversing layer in its entirety evaded record, a print was caught of some of its more prominent rays just before and after totality. The use of the prismatic camera was baffled by the anomalous scarcity of prominences.

Using an ingenious apparatus for viewing simultaneously the spectrum from both sides of the sun, Professor Hastings noticed at Caroline Island alternations, with the advance of the moon, in the respective heights above the right and left solar limbs of the coronal green line, which were thought to imply that the corona, with its rifts and sheaves and "tangled hanks" of rays, is, after all, merely an illusive appearance produced by the diffraction of sunlight at the moon's edge.[552] But the observation was assuredly misleading or misinterpreted. Atmospheric *diffusion* may indeed, under favouring circumstances, be effective in deceptively enlarging solar appendages; but always to a very limited extent.

The controversy is an old one as to the part played by our air in producing the radiance visible round the eclipsed sun. In its original form, it is true, it came to an end when Professor Harkness, in 1869,[553] pointed out that the shadow of the moon falls equally over the air and on the earth, and that if the sun had no luminous appendages, a circular space of almost absolute darkness would consequently surround the apparent places of the superposed sun and moon. Mr. Proctor,[554] with his usual ability, impressed this mathematically certain truth upon public attention; and Sir John Herschel calculated that the diameter of the "negative halo" thus produced would be, in general, no less than 23°.

But about the same time a noteworthy circumstance relating to the state of things in the solar vicinity was brought into view. On February 11, 1869, Messrs. Frankland and Lockyer communicated to the Royal Society a series of experiments on gaseous spectra under varying conditions of heat and density, leading them to the conclusion that the higher solar prominences exist in a medium of excessive tenuity, and that even at the base of the chromosphere the pressure is far below that at the earth's surface.[555] This inference was fully borne out by the researches of Wüllner; and Janssen expressed the opinion that the chromospheric gases are rarefied almost to the degree of an air-pump vacuum.[556] Hence was derived a general and fully justified conviction that there could be outside, and incumbent upon the chromosphere, no such vast atmosphere as the corona appeared to represent. Upon the strength of which conviction the "glare" theory entered, chiefly under the auspices of Sir Norman Lockyer, upon the second stage of its existence.

The genuineness of the "inner corona" to the height of 5′ or 6′ from the limb was admitted; but it was supposed that by the detailed reflection of its light in our air the far more extensive "outer corona" was optically created, the irregularities of the moon's edge being called in to account for the rays and rifts by which its structure was varied. This view received some countenance from Admiral Maclear's observation, during the eclipse of 1870, of bright lines "everywhere"—even at the centre of the lunar disc. Here, indeed, was an undoubted case of atmospheric diffusion; but here, also, was a safe index to the extent of its occurrence. Light scatters equally in all directions; so that when the moon's face at the time of an eclipse shows (as is the common case) a blank in the spectroscope, it is quite certain that the corona is not noticeably enlarged by atmospheric causes. A sky drifted over with thin cirrus clouds and air changed with aqueous vapour amply accounted for the abnormal amount of scattering in 1870.

But even in 1870 positive evidence was obtained of the substantial reality of the radiated outer corona, in the appearance on the photographic plates exposed by Willard in Spain and by Brothers in Sicily of identical dark rifts. The truth is, that far from being developed by misty air, it is peculiarly liable to be effaced by it. The purer the sky, the more extensive, brilliant, and intricate in the details of its structure the corona appears. Take as an example General Myer's description of the eclipse of 1869, as seen from the summit of White Top Mountain, Virginia, at an elevation above the sea of 5,523 feet, in an atmosphere of peculiar clearness.

"To the unaided eye," he wrote,[557] "the eclipse presented, during the total obscuration, a vision magnificent beyond description. As a centre stood the full and intensely black disc of the moon, surrounded by the aureola of a soft bright light, through which shot out, as if from the circumference of the moon, straight, massive, silvery rays, seeming distinct and separate from each other, to a distance of two or three diameters of the solar disc; the whole spectacle showing as on a background of diffused rose-coloured light."

On the same day, at Des Moines, Newcomb could perceive, through somewhat hazy air, no long rays, and the four-pointed outline of the corona reached at its farthest only a *single semidiameter* of the moon from the limb. The plain fact, that our atmosphere acts rather as a veil to hide the coronal radiance than as the medium through which it is visually formed, emerges from further innumerable records.

No observations of importance were made during the eclipse of September 9, 1885. The path of total obscurity touched land only on the shores of New Zealand, and two minutes was the outside limit of available time. Hence local observers had the phenomenon to themselves; nor were they even favoured by the weather in their efforts to make the most of it. One striking appearance was, however, disclosed. It was that of two "white" prominences of unusual brilliancy, shining like a pair of electric lamps hung one at each end of a solar diameter, right above the places of two large spots.[558] This coincidence of diametrically opposite disturbances is of too frequent occurrence to be accidental. M.

Trouvelot observed at Meudon, June 26, 1885, two active and evanescent prominences thus situated, each rising to the enormous height of 300,000 miles; and on August 16, one scarcely less remarkable, balanced by an antipodal spot-group.[559] It towered upward, as if by a process of *unrolling*, to a quarter of a million of miles; after which, in two minutes, the light died out of it; it had become completely extinct. The development, again from the ends of a diameter, of a pair of similar objects was watched, September 19 and 20, 1893, by Father Fényi, Director of the Kalocsa Observatory; and the phenomenon has been too often repeated to be accidental.

The eclipse of August 29, 1886, was total during about four minutes over tropical Atlantic regions; and an English expedition, led by Sir Norman Lockyer, was accordingly despatched to Grenada in the West Indies, for the purpose of using the opportunity it offered. But the rainy season was just then at its height: clouds and squalls were the order of the day; and the elaborately planned programme of observation could only in part be carried through. Some good work, none the less, was done. Professor Tacchini, who had been invited to accompany the party, ascertained besides some significant facts about prominences. From a comparison of their forms and sizes during and after the eclipse, it appeared that only the growing vaporous cores of these objects are shown by the spectroscope under ordinary circumstances; their upper sections, giving a faint continuous spectrum, and composed of presumably cooler materials, can only be seen when the veil of scattered light usually drawn over them is removed by an eclipse. Thus all modestly tall prominences have silvery summits; but all do not appear to possess the "red heart of flame," by which alone they can be rendered perceptible to daylight observation. Some prove to be ordinarily invisible, because silvery throughout—"sheeted ghosts," as it were, met only in the dark.

Specimens of the class had been noted as far back as 1842, but Tacchini first drew particular attention to them. The one observed by him in 1886 rose in a branching form to a height of 150,000 miles, and gave a brilliantly continuous spectrum, with bright lines at H and K, but no hydrogen-lines.[560] Hence the total invisibility of the object before and after the eclipse. During the eclipse, it was seen framed, as it were, in a pointed arch of coronal light, the symmetrical arrangement of which with regard to it was obviously significant. Both its unspringing shape, and the violet rays of calcium strongly emitted by it, contradicted the supposition that "white prominences" represent a downrush of refrigerated materials.

The corona of 1886, as photographed by Dr. Schuster and Mr. Maunder, showed neither the petals and plumes of 1871, nor the streamers of 1878. It might be called of a transition type.[561] Wide polar rifts were filled in with tufted radiations, and bounded on either side by irregularly disposed, compound luminous masses. In the south-western quadrant, a triangular ray, conspicuous to the naked eye, represented, Mr. W. H. Pickering thought, the projection of a huge, hollow cone.[562] Branched and recurving jets were curiously associated with it. The intrinsic photographic brightness of the corona proved, from Pickering's measures, to be about 1/54 that of the average surface of the full moon.

The Russian eclipse of August 19, 1887, can only be remembered as a disastrous failure. Much was expected of it. The shadow-path ran overland from Leipsic to the Japanese sea, so that the solar appurtenances would, it was hoped, be disclosed to observers echeloned along a line of 6,000 miles. But the incalculable element of weather rendered all forecasts nugatory. The clouds never parted, during the critical three minutes, over Central Russia, where many parties were stationed, and Professor D. P. Todd was equally unfortunate in Japan. Some good photographs were, nevertheless, secured by Professor Arai, Director of the Tokio Observatory, as well as by MM. Bélopolsky and Glasenapp at Petrovsk and Jurjevitch respectively. They showed a corona of simpler form than that of the year before, but not yet of the pronounced type first associated by Mr. Ranyard with the lowest stage of solar activity.

The genuineness of the association was ratified by the duplicate spectacle of the next-ensuing minimum year. Two total eclipses of the sun distinguished 1889. The first took place on New Year's Day, when a narrow shadow-path crossed California, allowing less than two minutes for the numerous experiments prompted by the varied nature of modern methods of research. American astronomers availed themselves of the occasion to the full. The heavens were propitious. Photographic records were obtained in unprecedented abundance, and of unusual excellence. Their comparison and study placed it beyond reasonable doubt that the radiated corona belonging to periods of maximum sun-spots gives place, at periods of minimum, to the "winged" type of 1878. Professor Holden perceived further that the equatorial extensions characterising the latter tend to assume a "trumpet-shape."[563] Their extremities diverge, as if mutually repellent, instead of flowing together along a medial plane. The maximum actinic brilliancy of the corona of January 1, 1889, was determined at Lick to be twenty-one times less than that of the full moon.[564] Its colour was described as "of an intense luminous silver, with a bluish tinge, similar to the light of an electric arc."[565] Its spectrum was comparatively simple. Very few bright lines besides those of hydrogen and coronium, and apparently no dark ones, stood out from the prismatic background.

"The marked structural features of the corona, as presented by the negatives" taken by Professors Nipher and Charroppin, were the filaments and the streamers. The filaments issued from polar calottes of 20° radius.

"The impression conveyed to the eye," Professor Pritchett wrote,[566] "is that the equatorial stream of denser coronal matter extends across and through the filaments, simply obscuring them by its greater brightness. The effect is just as if the equatorial belt were superposed upon, or passed through, the filamentary structure. There is nothing in the photographs to prove that the filaments do not exist all round the sun.[567] The testimony from negatives of different lengths of exposure goes to show that the equatorial streamers are made up of numerous interlacing parts inclined at varying angles to the sun's equator."

The coronal extensions, perceptible with the naked eye to a distance of more than 3° from the sun, appeared barely one-third of that length on the best negatives. Little more could be seen of them either in Barnard's exquisite miniature pictures, or in the photographs obtained by W. H. Pickering with a thirteen-inch refractor—the largest instrument so far used in eclipse-photography.

The total eclipse of December 22, 1889, held out a prospect, unfortunately not realized, of removing some of the doubts and difficulties that impeded the progress of coronal photography.[568] Messrs. Burnham and Schaeberle secured at Cayenne some excellent impressions, showing enough of the corona to prove its identical character with that depicted in the beginning of the year, but not enough to convey additional information about its terminal forms or innermost structure. Any better result was indeed impossible, the moisture-laden air having cut down the actinic power of the coronal light to one-fourth its previous value.

Two English expeditions organized by the Royal Astronomical Society fared still worse. Mr. Taylor was stationed on the West Coast of Africa, one hundred miles south of Loanda; Father Perry chose as the scene of his operations the Salut Islands, off French Guiana. Each was supplied with a reflector constructed by Dr. Common, endowed, by its extremely short focal length of forty-five, combined with an aperture of twenty inches, with a light-concentrating force capable, it was hoped, of compelling the very filmiest coronal branches to self-registration. Had things gone well two sets of coronal pictures, absolutely comparable in every respect, and taken at an interval of two hours and a half, would have been at the disposal of astronomers. But things went very far from well. Clouds altogether obscured the sun in Africa; they only separated to allow of his shining through a saturated atmosphere in South America. Father Perry's observations were the last heroic effort of a dying man. Stricken with malaria, he crawled to the hospital as soon as the eclipse was over, and expired five days later, at sea, on board the *Comus*. He was buried at Barbados. And the sacrifice of his life had, after all, purchased no decisive success. Most of the plates exposed by him suffered deterioration from the climate, or from an inevitably delayed development. A drawing from the best of them by Miss Violet Common[569] represented a corona differing from its predecessor of January 1, chiefly through the oppositely unsymmetrical relations of its parts. Then the western wing had been broader at its base than the eastern; now the inequality was conspicuously the other way.[570]

The next opportunity for retrieving the mischances of the past was offered April 16, 1893. The line of totality charted for that day ran from Chili to Senegambia. American parties appropriated the Andes; both shores of the Atlantic were in English occupation; French expeditions, led by Deslandres and Bigourdan, took up posts south of Cape Verde. A long totality of more than four minutes was favoured by serene skies; hence an ample store of photographic data was obtained. Professor Schaeberle, of the Lick Observatory, took, almost without assistance, at Mina Bronces, a mining station 6,600 feet above the Pacific, fifty-two negatives, eight of them with a forty-foot telescope, on a scale of four and a half inches to the solar diameter. Not only the inner corona, but the array of prominences then conspicuous, appeared in them to be composed of fibrous jets and arches, held to be sections of elliptic orbits described by luminous particles about the sun's centre.[571] One plate received the impression of a curious object,[572] entangled amidst coronal streamers, and the belief in its cometary nature was ratified by the bestowal of a comet-medal in recognition of the discovery. Similiar paraboloidal forms had, nevertheless, occasionally been seen to make an integral part of earlier coronas; and it remains extremely doubtful whether Schaeberle's "eclipse-comet" was justly entitled to the character claimed for it.

The eclipse of 1893 disclosed a radiated corona such as a year of spot-maximum was sure to bring. An unexpected fact about it was, however, ascertained. The coronal has been believed to have much in common with the chromospheric spectrum; it proved, on investigation with a large prismatic camera, employed under Sir Norman Lockyer's directions by Mr. Fowler at Fundium, to be absolutely distinct from it. The fundamental green ray had, on the West African plates, seven more refrangible associates;[573] but all alike are of unknown origin. They may be due to many substances, or to one; future research will perhaps decide; we can at present only say that the gaseous emission of the corona include none from hydrogen, helium, calcium, or any other recognisable terrestrial element. Deslandres' attempt to determine the rotation of the corona through opposite displacements, east and west of the interposed moon, of the violet calcium-lines supposed to make part of the coronal spectrum, was thus rendered nugatory. Yet it gave an earnest of success, by definitely introducing the subject into the constantly lengthened programme of eclipse-work. There is, however, little prospect of its being treated effectively until the green line is vivified by a fresh access of solar activity.

The flight of the moon's shadow was, on August 9, 1896, dogged by atrocious weather. It traversed, besides, some of the most inhospitable regions on the earth's surface, and afforded, at the best, but a brief interval of obscurity. At Novaya Zemlya, however, of all places, the conditions were tolerably favourable, and, as we have seen, the trophy of a "flash-spectrograph" was carried off. Some coronal photographs, moreover, taken by the late Sir George Baden-Powell[574] and by M. Hansky, a member of a Russian party, were marked by features of considerable interest. They made apparent a close connection between coronal outflows and chromospheric jets, cone-shaped beams serving as the sheaths, or envelopes, of prominences. M. Hansky,[575] indeed, thought that every streamer had a chromospheric eruption at its base. Further, dark veinings of singular shapes unmistakably interrupted the coronal light, and bordered brilliant prominences,[576] reminding us of certain "black lines" traced by Swift across the "anvil protuberance" August 7, 1869.[577] In type the corona of 1896 reproduced that of 1886, as befitted its intermediate position in the solar cycle.

The eclipse-track on January 22, 1898, crossed the Indian peninsula from Viziadrug, on the Malabar coast, to Mount Everest in the Himalayas. Not a cloud obstructed the view anywhere, and an unprecedented harvest of photographic records was garnered. The flash-spectrum, in its successive phases, appeared on plates taken by Sir Norman Lockyer, Mr. Evershed, Professor Campbell,[578] and others; Professor Turner[579] set on foot a novel mode of research by picturing the corona in the polarised ingredient of its light; Mrs. Maunder[580] practically solved the problem of photographing the faint coronal extensions, one ray on her plates running out to nearly six diameters from the moon's limb. Yet she used a Dallmeyer lens of only one and a half inches aperture. Her success accorded perfectly with Professor Wadsworth's conclusion that effectiveness in delineation by slight contrasts of luminosity varies inversely with aperture. Triple-coated plates, and a comparatively long exposure of twenty seconds, contributed to a result unlikely, for some time, to be surpassed. The corona of 1898 presented a mixed aspect. The polar plumes due at minimum were combined in it with the quadrilateral ogives belonging to spot-maxima. A slow course of transformation, in fact, seemed in progress; and it was found to be completed in 1900, when the eclipse of May 28 revealed the typical halo of a quiescent sun.

The obscurity on this occasion was short—less than 100 seconds—but was well observed east and west of the Atlantic. No striking gain in knowledge, however, resulted. Important experiments were indeed made on the heat of the corona with Langley's bolometer, but their upshot can scarcely be admitted as decisive. They indicated a marked deficiency of thermal radiations, implying for coronal light, in Professor Langley's opinion,[581] an origin analogous to that of the electric glow-discharge, which, at low pressures, was found by K. Ångström in 1893 to have no invisible heat-spectrum.[582] The corona was photographed by Professor Barnard, at Wadesborough, North Carolina, with a 61-1/2-foot horizontal "coelostat." In this instrument, of a type now much employed in eclipse operations and first recommended by Professor Turner, a six-inch photographic objective preserved an invariable position, while a silvered plane mirror, revolving by clockwork once in forty-eight hours (since the angle of movement is doubled by reflection), supplied the light it brought to a focus. A temporary wooden tube connected the lens with the photographic house where the plates were exposed. Pictures thus obtained with exposures of from one to fourteen seconds, were described as "remarkably sharp and perfectly defined, showing the prominences and inner corona very beautifully. The polar fans came out magnificently."[583]

The great Sumatra eclipse left behind it manifold memories of foiled expectations. A totality of above six minutes drew observers to the Far East from several continents, each cherishing a plan of inquiry which few were destined to execute. All along the line of shadow, which, on May 18, 1901, crossed Réunion and Mauritius, and again met land at Sumatra and Borneo, the meteorological forecast was dubious, and the meteorological actuality in the main deplorable. Nevertheless, the corona was seen, and fairly well photographed through drifting clouds, and proved to resemble in essentials the appendage viewed a year previously. Negatives taken by members of the Lick Observatory expedition led by Mr. Perrine[584] disclosed the unique phenomenon of a violent coronal disturbance, with a small compact prominence as its apparent focus. Tumbling masses and irregular streamers radiating from a point subsequently shown by the Greenwich photographs to be the seat of a conspicuous spot, suggested the recent occurrence of an explosion, the far-reaching effects of which might be traced in the confused floccular luminosity of a vast surrounding region. Again, photographs in polarised light attested the radiance of the outer corona to be in large measure reflected, while that of the inner ring was original; and the inference was confirmed by spectrographs, recording many Fraunhofer lines when the slit lay far from the sun's limb, but none in its immediate vicinity. On plates exposed by Mr. Dyson and Dr. Humphrys with special apparatus, the coronal spectrum, continuous and linear, impressed itself more extensively in the ultra-violet than on any previous occasion; and Dr. Mitchell succeeded in photographing the reversing layer by means of a grating spectroscope. Finally, Mrs. Maunder, at Mauritius, despite mischievous atmospheric tremors, obtained with the Newbegin telescope an excellent series of coronal pictures.[585]

The principles of explanation applied to the corona may be briefly described as eruptive and electrical. The first was adopted by Professor Schaeberle in his "Mechanical Theory," advanced in 1890.[586] According to this view, the eclipse-halo consists of streams of matter shot out with great velocity from the spot-zones by forces acting perpendicularly to the sun's surface. The component particles return to the sun after describing sections of extremely elongated ellipses, unless their initial speed happen to equal or exceed the critical rate of 383 miles a second, in which case they are finally driven off into space. The perspective overlapping and interlacing of these incandescent outflows was supposed to occasion the intricacies of texture visible in the corona; and it should be recorded that a virtually identical conclusion was reached by Mr. Perrine in 1901,[587] by a different train of reasoning, based upon a distinct set of facts. A theory on very much the same lines was, moreover, worked out by M. Bélopolsky in 1897.[588] Schaeberle, however, had the merit of making the first adequate effort to deduce the real shape of the corona, as it exists in three dimensions, from its projection upon the surface of the sphere. He failed, indeed, to account for the variation in coronal types by the changes in our situation with regard to the sun's equator. It is only necessary to remark that, if this were so, they should be subject to an annual periodicity, of which no trace can be discerned.

Electro-magnetic theories have the charm, and the drawback, of dealing largely with the unknown. But they are gradually losing the vague and intangible character which long clung to them; and the improved definition of their outlines has not, so far, brought them into disaccord with truth. The most promising hypothesis of the kind is due to Professor Bigelow of Washington. His able discussion of the eclipse photographs of January 1, 1889,[589] showed a striking agreement between the observed coronal forms and the calculated effects of a repulsive influence obeying the laws of electric potential, also postulated by Huggins in 1885.[590] Finely subdivided matter, expelled from the sun along lines of force emanating from the neighbourhood of his poles, thus tends to accumulate at "equipotential surfaces." In deference, however, to a doubt more strongly felt then than now, whether the presence of free electricity is compatible with the solar temperature, he avoided any express assertion that the coronal structure is an electrical phenomenon, merely pointing out that, if it were, its details would be just what they are.

Later, in 1892, Pupin in America,[591] and Ebert in Germany,[592] imitated the coronal streamers by means of electrical discharges in low vacua between small conducting bodies and strips of tinfoil placed on the outside of the containing glass receptacles. Finally, a critical experiment made by Ebert in 1895 served, as Bigelow justly said, "to clear up the entire subject, and put the theory on a working basis." Having obtained coronoidal effects in the manner described, he proceeded to subject them to the action of a strong magnetic field, with the result of marshalling the scattered rays into a methodical and highly suggestive array. They followed the direction of the magnetic lines of force, and, forsaking the polar collar of the magnetised sphere, surrounded it like a ruffle. The obvious analogy with the aurora polaris and the solar corona was insisted upon by Ebert himself, and has been further developed by Bigelow.[593] According to a recent modification of his hypothesis, the latter appendage is controlled by two opposing systems of forces; the magnetic causing the rays to diverge from the poles towards the equator, and the electrostatic urging their spread, through the mutual repulsion of the particles accumulated in the "wings," from the equator towards either pole. The cyclical change in the corona, he adds, is probably due to a variation in the balance of power thus established, the magnetic polar influence dominating at minima, the electrostatic at maxima. And he may well feel encouraged by the fortunate combination of many experimental details into one explanatory whole, no less than by the hopeful prospect of further developments, both practical and theoretical, along the same lines.

What we really know about the corona can be summed up in a few words. It is certainly *not* a solar atmosphere. It does not gravitate upon the sun's surface and share his rotation, as our air gravitates upon and shares the rotation of the earth; and this for the simple reason that there is no visible growth of pressure downwards (of which the spectroscope would infallibly give notice) in its gaseous constituents; whereas under the sole influence of the sun's attractive power, their density should be multiplied many million times in the descent through a mere fraction of their actual depth.[594]

They are apparently in a perpetual state of efflux from, and influx to our great luminary, under the stress of opposing forces. It is not unlikely that some part, at least, of the coronal materials are provided by eruptions from the body of the sun;[595] it is almost certain that they are organized and arranged round it through electro-magnetic action. This, however, would seem to be influential only upon their white-hot or reflective ingredients, out of which the streamers and aigrettes are composed; since the coronal gases appear, from observations during eclipses, to form a shapeless envelope, with condensations above the spot-zones, or at the bases of equatorial extensions. The corona is undoubtedly affected both in shape and constitution by the periodic ebb and flow of solar activity, its low-tide form being winged, its high-tide form stellate; while the rays emitted by the gases contained in it fade, and the continuous spectrum brightens, at times of minimum sun-spots. The appendage, as a whole, must be of inconceivable tenuity, since comets cut their way through it without experiencing sensible retardation. Not even Sir William Crookes's vacua can give an idea of the rarefaction which this fact implies. Yet the observed luminous effects may not in reality bear witness contradictory of it. One solitary molecule in each cubic inch of space might, in Professor Young's opinion, produce them; while in the same volume of ordinary air at the sea-level, the molecules number (according to Dr. Johnstone Stoney) 20,000 trillions!

The most important lesson, however, derived from eclipses is that of partial independence of them. Some of its fruits in the daily study of prominences the next chapter will collect; and the harvest has been rendered more abundant, as well as more valuable, since it has been found possible to enlist, in this department too, the versatile aid of the camera.

FOOTNOTES:

[512] *Vierteljahrsschrift Astr. Ges.*, Jahrg. xxvi., p. 274.

[513] *Astr. Jour.*, vol. iv., p. 33.

[514] *Proc. Roy. Soc.*, vol. xvii., p. 116.

[515] *Comptes Rendus*, t. lxvii., p. 757.

[516] *Comptes Rendus*, t. lxvii., p. 839.

[517] *Month. Not.*, vol. xxvii., p. 88.

[518] *Proc. Roy. Soc.*, vol. xvii., p. 123.

[519] *Washington Observations*, 1867, App. ii., Harkness's Report, p. 60.

[520] *Am. Jour.*, vol. xlviii. (2nd series), p. 377.

[521] *Am. Jour.*, vol. xi. (3rd series), p. 429.

[522] Campbell, *Astroph. Jour.*, vol. x., p. 186.

[523] Keeler, *Reports on Eclipse of January 1, 1889*, p. 47.

[524] Everything in such observations depends upon the proper manipulation of the slit of the spectroscope.

[525] *Mem. R. A. S.*, vol. xli., p. 435.

[526] *Comptes Rendus*, t. lxvii., p. 1019.

[527] *Mem. R. A. S.*, vol. xli., p. 43.

[528] *Comptes Rendus*, t. xciv., p. 1640.

[529] Young, *Pop. Astr.*, Oct., 1897, p. 333.

[530] J. Evershed, *Indian Eclipse*, 1898, p. 65; *Month. Not.*, vol. lviii., p. 298; *Proc. Roy. Soc.*, Jan. 17, 1901.

[531] Frost, *Astroph. Jour.*, vol. xii., p. 85; Lord, *Ibid.*, vol. xiii., p. 149.

[532] *Comptes Rendus*, t. cxvii., No. 1; *Jour. Brit. Astr. Ass.*, vol. iii., p. 532.

[533] Lockyer, *Phil. Trans.*, vol. clvii., p. 551.

[534] The rosy envelope of prominence-matter was so named by Lockyer in 1868 (*Phil. Trans.*, vol. clix., p. 430).

[535] According to Trouvelot (*Wash. Obs.*, 1876, App. iii., p. 80), the subtracted matter was, at least to some extent, accumulated in the polar regions.

[536] *Bull. Phil. Soc. Washington*, vol. iii., p. 118.

[537] *Mem. R. A. S.*, vol. xli., 1879.

[538] *Astr. Nach.*, No. 1,737.

[539] *Correspondence with Newton*, pp. 181-184; Ranyard, *Mem. Astr. Soc.*, vol. xli., p. 501.

[540] S. P. Langley, *Wash. Obs.*, 1876, App. iii., p. 209; *Nature*, vol. lxi., p. 443.

[541] Schuster (*Proc. Roy. Soc.*, vol. xxxv., p. 154) measured and photographed about thirty.

[542] Abney, *Phil. Trans.*, vol. clxxv., p. 267.

[543] *Proc. Roy. Soc.*, vol. xxxiv., p. 409. Experiments directed to the same end had been made by Dr. O. Lohse at Potsdam, 1878-80. *Astr. Nach.*, No. 2,486.

[544] The sensitiveness of chloride of silver extends from *h* to H; that is, over the upper or more refrangible half of the space in which the main part of the coronal light is concentrated.

[545] *Proc. Roy. Soc.*, vol. xxxiv., p. 414.

[546] *Report Brit. Assoc.*, 1883, p. 351.

[547] Maunder, *Indian Eclipse*, p. 125; *Eclipse of 1900*, p. 143.

[548] *Astr. and Astrophysics*, vol. xiii., p. 662.

[549] See *infra*, p. 197.

[550] Abney, *Phil. Trans.*, vol. clxxx., p. 119.

[551] *Comptes Rendus*, t. xcvii., p. 592.

[552] *Memoirs National Ac. of Sciences*, vol. ii., p. 102.

[553] *Wash. Obs.*, 1867, App. ii., p. 64.

[554] *The Sun*, p. 357.

[555] *Proc. Roy. Soc.*, vol. xvii., p. 289.

[556] *Comptes Rendus*, t. lxxiii., p. 434.

[557] *Wash. Obs.*, 1867, App. ii., p. 195.

[558] Stokes, Anniversary Address, *Nature*, vol. xxxv., p. 114.

[559] *Comptes Rendus*, t. ci., p. 50.

[560] *Harvard Annals*, vol. xviii., p. 99.

[561] Wesley, *Phil. Trans.*, vol. clxxx., p. 350.

[562] *Harvard Annals*, vol. xviii, p. 108.

[563] *Lick Report*, p. 20.

[564] *Ibid.*, p. 14.

[565] *Ibid.*, p. 155.

[566] *Pub. Astr. Soc. of the Pacific*, vol. iii., p. 158.

[567] Professor Holden concluded, with less qualification, “that so-called ‘polar’ rays exist at all latitudes on the sun’s surface.” *Lick Report*, p. 19.

[568] Holden, *Report on Eclipse of December, 1889*, p. 18; Charroppin, *Pub. Astr. Soc. of the Pacific*, vol. iii., p. 26.

[569] Published as the Frontispiece to the *Observatory*, No. 160.

[570] Wesley, *Ibid.*, p. 107.

[571] *Lick Observatory Contributions*, No. 4, p. 108.

[572] *Astr. and Astrophysics*, vol. xiii. p. 307.

[573] Lockyer, *Phil. Trans.*, vol. clxxxvii., p. 592.

[574] He died in London, November 20, 1898.

[575] *Bull. Acad. St. Pétersbourg*, t. vi., p. 253.

[576] W. H. Wesley, *Phil. Trans.*, vol. cxc, p. 204.

[577] *Lick Reports on Eclipse of January 1, 1889*, p. 204.

[578] *Astroph. Jour.*, vol. xi., p. 226.

[579] *Observatory*, vol. xxi., p. 157.

[580] *The Indian Eclipse*, 1898, p. 114.

[581] *Science*, June 22, 1900; *Astroph. Jour.*, vol. xii., p. 370.

[582] *Ann. der Physik*, Bd. xlviii., p. 528. See also Wood, *Physical Review*, vol. iv., p. 191, 1896.

[583] *Science*, August 3, 1900.

[584] *Lick Observatory Bulletin*, No. 9.

[585] *Observatory*, vol. xxiv., pp. 321, 375.

[586] *Lick Report on Eclipse of December 22, 1889*, p. 47; *Month. Not.*, vol. l., p. 372.

[587] *Lick Obs. Bull.*, No. 9.

[588] *Bull. de l’Acad. St. Pétersbourg*, t. iv., p. 289.

[589] *The Solar Corona discussed by Spherical Harmonics*, Smithsonian Institution, 1889.

[590] Bakerian Lecture, *Proc. Roy. Soc.*, vol. xxxix.

[591] *Astr. and Astrophysics*, vol. xi., p. 483.

[592] *Ibid.*, vol. xii., p. 804.

[593] *Am. Journ. of Science*, vol. xi., p. 253, 1901.

[594] See Huggins, *Proc. Roy. Soc.*, vol. xxxix., p. 108; Young, *North Am. Review*, February, 1885, p. 179.

[595] Professor W. A. Norton, of Yale College, appears to have been the earliest formal advocate of the Expulsion Theory of the solar surroundings, in the second (1845) and later editions of his *Treatise on Astronomy*.

CHAPTER IV

SOLAR SPECTROSCOPY

The new way struck out by Janssen and Lockyer was at once and eagerly followed. In every part of Europe, as well as in North America, observers devoted themselves to the daily study of the chromosphere and prominences. Foremost among these were Lockyer in England, Zöllner at Leipzig, Spörer at Anclam, Young at Hanover, New Hampshire, Secchi and Respighi at Rome. There were many others, but these names stood out conspicuously.

The first point to be cleared up was that of chemical composition. Leisurely measurements verified the presence above the sun's surface of hydrogen in prodigious volumes, but showed that sodium had nothing to do with the orange-yellow ray identified with it in the haste of the eclipse. From its vicinity to the D-pair (than which it is slightly more refrangible), the prominence-line was, however, designated D_3, and the unknown substance emitting it was named by Lockyer "helium." Its terrestrial discovery ensued after twenty-six years. In March, 1895, Professor Ramsay obtained from the rare mineral clevite a volatile gas, the spectrum of which was found to include the yellow prominence-ray. Helium was actually at hand, and available for examination. The identification cleared up many obscurities in chromospheric chemistry. Several bright lines, persistently seen at the edge of the sun, and early suspected by Young[596] to emanate from the same source as D_3, were now derived from helium in the laboratory; and all the complex emissions of that exotic substance ranged themselves into six sets or series, the members of which are mutually connected by numerical relations of a definite and simple kind. Helium is of rather more than twice the density of hydrogen, and has no chemical affinities. In almost evanescent quantities it lurks in the earth's crust, and is diffused through the earth's atmosphere.

The importance of the part played in the prominence-spectrum by the violet line of calcium was noticed by Professor Young in 1872, but since H and K lie near the limit of the visible spectrum, photography was needed for a thorough investigation of their appearances. Aided by its resources, Professor George E. Hale, then at the beginning of his career, detected in 1889 their unfailing and conspicuous presence.[597] The substance emitting them not only constitutes a fundamental ingredient of the chromosphere, but rises, in the fantastic jets thence issuing, to greater heights than hydrogen itself. The isolation of H and K in solar prominences from any other of the lines usually distinctive of calcium was experimentally proved by Sir William and Lady Huggins in 1897 to be due to the extreme tenuity of the emitting vapour.[598]

Hydrogen, helium, and calcium form, then, the chief and unvarying materials of the solar sierra and its peaks; but a number of metallic elements make their appearance spasmodically under the influence of disturbances in the layers beneath. In September, 1871, Young[599] drew up at Dartmouth College a list of 103 lines significant of injections into the chromosphere of iron, titanium, chromium, magnesium, and many other substances. During two months' observation in the pure air of Mount Sherman (8,335 feet high) in the summer of 1872, these tell-tale lines mounted up to 273;[600] and he believes their number might still be doubled by steady watching. Indeed, both Young and Lockyer have more than once seen the whole field of the spectroscope momentarily inundated with bright rays, as if the "reversing layer" had been suddenly thrust upwards into the chromosphere, and as quickly allowed to drop back again. The opinion would thus appear to be well-grounded that the two form one continuous region, of which the lower parts are habitually occupied by the heaviest vapours, but where orderly arrangement is continually overturned by violent eruptive disturbances.

The study of the *forms* of prominences practically began with Huggins's observation of one through an "open slit" February 13, 1869.[601] At first it had been thought possible to examine them only in sections—that is, by admitting mere narrow strips or "lines" of their various kinds of light; while the actual shape of the objects emitting those lines had been arrived at by such imperfect devices as that of giving to the slit of the spectroscope a vibratory moment rapid enough to enable the eye to retain the impression of one part while others were successively presented to it. It was an immense gain to find that their rays had strength to bear so much of dilution with ordinary light as was involved in opening the spectroscopic shutter wide enough to exhibit the tree-like, or horn-like, or flame-shaped bodies rising over the sun's rim in their undivided proportions. Several diversely-coloured images of them are formed in the spectroscope; each may be seen under a crimson, a yellow, a green, and a deep blue aspect. The crimson, however (built up out of the C-line of hydrogen), is the most intense, and is commonly used for purposes of observation and illustration.

Friedrich Zöllner was, by a few days, beforehand with Huggins in describing the open-slit method, but was somewhat less prompt in applying it. His first survey of a complete prominence, pictured in, and not simply intersected by, the slit of his spectroscope, was obtained July 1, 1869.[602] Shortly afterwards the plan was successfully adopted by the whole band of investigators.

A difference in kind was very soon perceived to separate these objects into two well-marked classes. Its natural and obvious character was shown by its having struck several observers independently. The distinction of "cloud-prominences" from "flame-prominences" was announced by Lockyer, April 27; by Zöllner, June 2; and by Respighi, December 4, 1870.

The first description are tranquil and relatively permanent, sometimes enduring without striking change for many days. Certain of the included species mimic terrestrial cloud-scenery—now appearing like fleecy cirrus transpenetrated with the red glow of sunset—

now like prodigious masses of cumulo-stratus hanging heavily above the horizon. The solar clouds, however, have the peculiarity of possessing *stems*. Slender columns can ordinarily be seen to connect the surface of the chromosphere with its outlying portions. Hence the fantastic likeness to forest scenery presented by the long ranges of fiery trunks and foliage occasionally seeming to fringe the sun's limb. But while this mode of structure suggests an actual outpouring of incandescent material, certain facts require a different interpretation. At a distance, and quite apart from the chromosphere, prominences have been perceived, both by Secchi and Young, to *form*, just as clouds form in a clear sky, condensation being replaced by ignition. Filaments were then thrown out downward towards the chromosphere, and finally the usual appearance of a "stemmed prominence" was assumed. Still more remarkable was an observation made by Trouvelot at Harvard College Observatory, June 26, 1874.[603] A gigantic comma-shaped prominence, 82,000 miles high, vanished from before his eyes by a withdrawal of light as sudden as the passage of a flash of lightning. The same observer has frequently witnessed a gradual illumination or gradual extinction of such objects, testifying to changes in the thermal or electrical condition of matter already *in situ*.

The first photograph of a prominence, as shown by the spectroscope in daylight, was taken by Professor Young in 1870.[604] But neither his method, nor that described by Dr. Braun in 1872,[605] had any practical success. This was reserved to reward the efforts towards the same end of Professor Hale. Begun at Harvard College in 1889,[606] they were prosecuted soon afterwards at the Kenwood Observatory, Chicago. The great difficulty was to extricate the coloured image of the gaseous structure, spectroscopically visible at the sun's limb, from the encompassing glare, a very little of which goes a long way in *fogging* sensitive plates. To counteract its mischievous effects, a second slit,[607] besides the usual narrow one in front of the collimator, was placed on guard, as it were, behind the dispersing apparatus, so as to shut out from the sensitised surface all light save that of the required quality. The sun's image being then allowed to drift across the outer slit, while the plate holder was kept moving at the same rate, the successive sectional impressions thus rapidly obtained finally "built up" a complete picture of the prominence. Another expedient was soon afterwards contrived.[608] The H and K rays of calcium are always, as we have seen, bright in the spectrum of prominences. They are besides fine and sharp, while the corresponding absorption-lines in the ordinary solar spectrum are wide and diffuse. Hence, prominences formed by the spectroscope out of these particular qualities of violet light, can be photographed entire and at once, for the simple reason that they are projected upon a naturally darkened background. Atmospheric glare is abolished by local absorption. This beautiful method was first realised by Professor Hale in June, 1891.

A "spectroheliograph," consisting of a spectroscopic and a photographic apparatus of special type, attached to the eye-end of an equatoreal twelve inches in aperture, was erected at Kenwood in March, 1891; and with its aid, Professor Hale entered upon original researches of high promise for the advancement of solar physics. Noteworthy above all is his achievement of photographing both prominences and faculæ on the very face of the sun. The latter had, until then, been very imperfectly observed. They were only visible, in fact, when relieved by their brilliancy against the dusky edge of the solar disc. Their convenient emission of calcium light, however, makes it possible to photograph them in all positions, and emphasises their close relationship to prominences. The simultaneous picturing, moreover, of the entire chromospheric ring, with whatever trees or fountains of fire chance to be at the moment issuing from it, has been accomplished by a very simple device. The disc of the sun itself having been screened with a circular metallic diaphragm, it is only necessary to cause the slit to traverse the virtually eclipsed luminary, in order to get an impression of the whole round of its fringing appendages. And the record can be extended to the disc by removing the screen, and carrying the slit back at a quicker rate, when an "image of the sun's surface, with the faculæ and spots, is formed on the plate exactly within the image of the chromosphere formed during the first exposure. The whole operation," Professor Hale continues, "is completed in less than a minute, and the resulting photographs give the first true pictures of the sun, showing all of the various phenomena at its surface."[609] Most of these novel researches were, by a remarkable coincidence, pursued independently and contemporaneously by M. Deslandres, of the Paris Observatory.[610]

The ultra-violet prominence spectrum was photographed for the first time from an uneclipsed sun, in June, 1891, at Chicago. Besides H and K, four members of the Huggins-series of hydrogen-lines imprinted themselves on the plate.[611] Meanwhile M. Deslandres was enabled, by fitting quartz lenses to his spectroscope, and substituting a reflecting for a refracting telescope, to get rid of the obstructive action of glass upon the shorter light-waves, and thus to widen the scope of his inquiry into the peculiarities of those derived from prominences.[612] As the result, not only all the nine white-star lines were photographed from a brilliant sun-flame, but five additional ones were found to continue the series upward. The wave-lengths of these last had, moreover, been calculated beforehand with singular exactness, from a simple formula known as "Balmer's Law."[613] The new lines, accordingly, filled places in a manner already prepared for them, and were thus unmistakably associated with the hydrogen-spectrum. This is now known to be represented in prominences by twenty-seven lines,[614] forming a kind of harmonic progression, only

PLATE I.

Photographs of the Solar Chromosphere and Prominences.
Taken with the Spectroheliograph of the Kenwood Observatory, Chicago, by Professor George E. Hale.

four of which are visibly darkened in the Fraunhofer spectrum of the sun.

The chemistry of “cloud-prominences” is simple. Hydrogen, helium, and calcium are their chief constituents. “Flame-prominences,” on the other hand, show, in addition, the characteristic rays of a number of metals, among which iron, titanium, barium, strontium, sodium, and magnesium are conspicuous. They are intensely brilliant; sharply defined in their varying forms of jets, spikes, fountains, waterspouts; of rapid formation and speedy dissolution, seldom attaining to the vast dimensions of the more tranquil kind. Eruptive or explosive by origin, they occur in close connection with spots; whether causally, the materials ejected as “flames” cooling and settling down as dark, depressed patches of increased absorption;[615] or consequentially, as a reactive effect of falls of solidified substances from great heights in the solar atmosphere.[616] The two classes of phenomena, at any rate, stand in a most intimate relation; they obey the same law of periodicity, and are confined to the same portions of the sun’s surface, while quiescent prominences may be found right up to the poles and close to the equator.

The general distribution of prominences, including both genera, follows that of faculæ much more closely than that of spots. From Father Secchi’s and Professor Respighi’s observations, 1869-71, were derived the first clear ideas on the subject, which have been supplemented and modified by the later researches of Professors Tacchini and Riccò at Rome and Palermo. The results are somewhat complicated, but may be stated broadly as follows. The district of greatest prominence-frequency covers and overlaps by several degrees that of the greatest spot-frequency. That is to say, it extends to about 40° north and south of the equator.[617] There is a visible tendency to a second pair of maxima nearer the poles. The poles themselves, as well as the equator, are regions of minimum occurrence. Distribution in time is governed by the spot-cycle, but the maximum lasts longer for prominences than for spots.

The structure of the chromosphere was investigated in 1869 and subsequent years by Professor Respighi, director of the Capitoline Observatory, as well as by Spörer, and Brédikhine of the Moscow Observatory. They found this supposed solar envelope to be of the same eruptive nature as the vast protrusions from it, and to be made up of a congeries of minute flames[618] set close together like blades of grass. “The appearance,” Professor Young writes,[619] “which probably indicates a fact, is as if countless jets of heated gas were issuing through vents and spiracles over the whole surface, thus clothing it with flame which heaves and tosses like the blaze of a conflagration.”

The summits of these filaments of fire are commonly inclined, as if by a wind sweeping over them, when the sun’s activity is near its height, but erect during his phase of tranquillity. Spörer, in 1871, inferred the influence of permanent polar currents,[620] but Tacchini showed in 1876 that the deflections upon which this inference was based ceased to be visible as the spot-minimum drew near.[621]

Another peculiarity of the chromosphere, denoting the remoteness of its character from that of a true atmosphere,[622] is the irregularity of its distribution over the sun's surface. There are no signs of its bulging out at the equator, as the laws of fluid equilibrium in a rotating mass would require; but there are some that the fluctuations in its depth are connected with the phases of solar agitation. At times of minimum it seems to accumulate and concentrate its activity at the poles; while maxima probably bring a more equable general distribution, with local depressions at the base of great prominences and above spots.

A low-lying stratum of carbon-vapour was, in 1897, detected in the chromosphere by Professor Hale with a grating-spectroscope attached to the 40-inch Yerkes refractor.[623] The eclipse-photographs of 1893 disclosed to Hartley's examination the presence there of gallium;[624] and those taken by Evershed in 1898 were found by Jewell[625] to be crowded with ultra-violet lines of the equally rare metal scandium. The general rule had been laid down by Sir Norman Lockyer that the metallic radiations from the chromosphere are those "enhanced" in the electric spark.[626] Hence, the comparative study of conditions prevalent in the arc and the spark has acquired great importance in solar physics.

The reality of the appearance of violent disturbance presented by the "flaming" kind of prominence can be tested in a very remarkable manner. Christian Doppler,[627] professor of mathematics at Prague, enounced in 1842 the theorm that the colour of a luminous body, like the pitch of a sonorous body, must be changed by movements of approach or recession. The reason is this. Both colour and pitch are physiological effects, depending, not upon absolute wave-length, but upon the number of waves entering the eye or ear in a given interval of time. And this number, it is easy to see, must be increased if the source of light or sound is diminishing its distance, and diminished if it is decreasing it. In the one case, the vibrating body *pursues* and crowds together the waves emanating from it; in the other, it *retreats* from them, and so lengthens out the space covered by an identical number. The principle may be thus illustrated. Suppose shots to be fired at a target at fixed intervals of time. If the marksman advances, say twenty paces between each discharge of his rifle, it is evident that the shots will fall faster on the target than if he stood still; if, on the contrary, he retires by the same amount, they will strike at correspondingly longer intervals. The result will of course be the same whether the target or the marksman be in movement.

So far Doppler was altogether right. As regards sound, anyone can convince himself that the effect he predicted is a real one, by listening to the alternate shrilling and sinking of the steam-whistle when an express train rushes through a station. But in applying this principle to the colours of stars he went widely astray; for he omitted from consideration the double range of invisible vibrations which partake of, and to the eye exactly compensate, changes of refrangibility in the visible rays. There is, then, no possibility of finding a criterion of velocity in the hue of bodies shining, like the sun and stars, with continuous light. The entire spectrum is slightly shifted up or down in the scale of refrangibility; certain rays normally visible become exalted or degraded (as the case may be) into invisibility, and certain other rays at the opposite end undergo the converse process; but the sum total of impressions on the retina continues the same.

We are not, however, without the means of measuring this sub-sensible transportation of the light-gamut. Once more the wonderful Fraunhofer lines came to the rescue. They were called by the earlier physicists “fixed lines;” but it is just because they are *not* fixed that, in this instance, we find them useful. They share, and in sharing betray, the general shift of the spectrum. This aspect of Doppler’s principle was adverted to by Fizeau in 1848,[628] and the first tangible results in the estimation of movements of approach and recession between the earth and the stars, were communicated by Sir William Huggins to the Royal Society, April 23, 1868. Eighteen months later, Zöllner devised his “reversion-spectroscope”[629] for doubling the measurable effects of line-displacements; aided by which ingenious instrument, and following a suggestion of its inventor, Professor H. C. Vogel succeeded at Bothkamp, June 9, 1871,[630] in detecting effects of that nature due to the solar rotation. This application constitutes at once the test and the triumph of the method.[631]

The eastern edge of the sun is continually moving towards us with an equatorial speed of about a mile and a quarter per second, the western edge retreating at the same rate. The displacements—towards the violet on the east, towards the red on the west—corresponding to this velocity are very small; so small that it seems hardly credible that they should have been laid bare to perception. They amount to but 1/150th part of the interval between the two constituents of the D-line of sodium; and the D-line of sodium itself can be separated into a pair only by a powerful spectroscope. Nevertheless, Professor Young[632] was able to show quite satisfactorily, in 1876, not only deviations in the solar lines from their proper places indicating a velocity of rotation (1·42 miles per second) slightly in excess of that given by observations of spots, but the exemption of terrestrial lines (those produced by absorption in the earth’s atmosphere) from the general push upwards or downwards. Shortly afterwards, Professor Langley, then director of the Allegheny Observatory, having devised a means of comparing with great accuracy light from different portions of the sun’s disc, found that while the obscure rays in two juxtaposed spectra derived from the solar poles were absolutely continuous, no sooner was the instrument rotated through 90°, so as to bring its luminous supplies from opposite extremities of the equator, than the same rays became perceptibly “notched.” The telluric lines, meanwhile, remained unaffected, so as to be “virtually mapped” by the process.[633] This rapid and unfailing mode of distinction was used by Cornu with perfect ease during his investigation of atmospheric absorption near Loiret in August and September, 1883.

[634]

A beautiful experiment of the same kind was performed by M. Thollon, of M. Bischoffsheim's observatory at Nice, in the summer of 1880.[635] He confined his attention to one delicately defined group of four lines in the orange, of which the inner pair are solar (iron) and the outer terrestrial. At the centre of the sun the intervals separating them were sensibly equal; but when the light was taken alternately from the right and left limbs, a relative shift in alternate directions of the solar, towards and from the stationary telluric rays became apparent. A parallel observation was made at Dunecht, December 14, 1883, when it was noticed that a strong iron-line in the yellow part of the solar spectrum is permanently double on the sun's eastern, but single on his western limb;[636] opposite motion-displacements bringing about this curious effect of coincidence with, and separation from, an adjacent stationary line of our own atmosphere's production, according as the spectrum is derived from the retreating or advancing margin of the solar globe. Statements of fact so precise and authoritative amount to a demonstration that results of this kind are worthy of confidence; and they already occupy an important place among astronomical data.

The subtle method of which they served to assure the validity was employed in 1887-9 by M. Dunér to test and extend Carrington's and Spörer's conclusions as to the anomalous nature of the sun's axial movement.[637] His observations for the purpose, made with a fine diffraction-spectroscope, just then mounted at the observatory of Upsala, were published in 1891.[638] Their upshot was to confirm and widen the law of retardation with increasing latitude derived from the progressive motions of spots. Determinations made within 15° of the pole, consequently far beyond the region of spots, gave a rotation-period of 38-1/2, that of the equatorial belt being of 25-1/2 days. Spots near the equator indeed complete their rounds in a period shorter by at least half a day; and proportionate differences were found to exist elsewhere in corresponding latitudes; but Dunér's observations, it must be remembered, apply to a distinct part of the complex solar machine from the disturbed photospheric surface. It is amply possible that the absorptive strata producing the Fraunhofer lines, significant, by their varying displacements at either limb, of the inferred varying rates of rotation, may gyrate more slowly than the spot-generating level. Moreover, faculæ appear to move at a quicker pace than either;[639] so that we have, for three solar formations, three different periods of average rotation, the shortest of which belongs to the faculæ, one of intermediate length to the spots, and the most protracted to the reversing layer. All, however, agree in lengthening progressively from the equator towards the poles. Professor Holden aptly compared the sun to "a vast whirlpool where the velocities of rotation depend not only on the situation of the rotating masses as to latitude, but also as to depth beneath the exterior surface."[640]

Sir Norman Lockyer[641] promptly perceived the applicability of the surprising discovery of line-shiftings through end-on motion to the study of prominences, the discontinuous light of which affords precisely the same means of detecting movement without seeming change of place, as do lines of absorption in a continuous spectrum. Indeed, his observations at the sun's edge almost compelled recourse to an explanation made available just when the need of it began to be felt. He saw bright lines, not merely pushed aside from their normal places by a barely perceptible amount, but bent, torn, broken, as if by the stress of some tremendous violence. These remarkable appearances were quite simply interpreted as the effects of movements varying in amount and direction in the different parts of the extensive mass of incandescent vapours falling within a single field of view. Very commonly they are of a cyclonic character. The opposite distortions of the same coloured rays betray the fury of "counter-gales" rushing along at the rate of 120 miles a second; while their undisturbed sections prove the persistence of a "heart of peace" in the midst of that unimaginable fiery whirlwind. Velocities up to 250 *miles a second*, or 15,000 times that of an express train at the top of its speed, were thus observed by Young during his trip to Mount Sherman, August 2, 1872; and these were actually doubled in an extraordinary outburst observed by Father Jules Fényi, on June 17, 1891, at the Haynald Observatory in Hungary, as well as by M. Trouvelot at Meudon.[642]

Motions ascertainable in this way near the limb are, of course, horizontal as regards the sun's surface; the analogies they present might, accordingly, be styled *meteorological* rather than *volcanic*. But vertical displacements on a scale no less stupendous can also be shown to exist. Observations of the spectra of spots centrally situated (where motions in the line of sight are vertical) disclose the progress of violent uprushes and downrushes of ignited gases, for the most part in the penumbral or outlying districts. They appear to be occasioned by fitful and irregular disturbances, and have none of the systematic quality which would be required for the elucidation of sun-spot theories. Indeed, they almost certainly take place at a great height above the actual openings in the photosphere.

As to vertical motions above the limb, on the other hand, we have direct visual evidence of a truly amazing kind. The projected glowing matter has, by the aid of the spectroscope, been watched in its ascent. On September 7, 1871, Young examined at noon a vast hydrogen cloud 100,000 miles long, as it showed to the eye, and 54,000 high. It floated tranquilly above the chromosphere at an elevation of some 15,000 miles, and was connected with it by three or four upright columns, presenting the not uncommon aspect compared by Lockyer to that of a grove of banyans. Called away for a few minutes at 12.30, on returning at 12.55 the observer found—

"That in the meantime the whole thing had been literally blown to shreds by some inconceivable uprush from beneath. In place of the quiet cloud I had left, the air, if I may use the expression, was filled with flying débris—a mass of detached, vertical, fusiform filaments, each from 10′ to 30′ long by 2′ or 3′ wide,[643] brighter and closer together where the pillars had formerly stood, and rapidly ascending. They rose, with a velocity estimated at 166 miles a second, to fully 200,000 miles above the sun's surface, then gradually faded away like a dissolving cloud, and at 1.15 only a few filmy wisps, with some brighter streamers low down near the photosphere, remained to mark the place."[644]

A velocity of projection of *at least* 500 miles per second was, by Proctor's[645] calculation, required to account for this extraordinary display, to which the earth immediately responded by a magnetic disturbance, and a fine aurora. It has proved by no means an isolated occurrence. Young saw its main features repeated, October 7, 1881,[646] on a still vaster scale; for the exploded prominence attained, this time, an altitude of 350,000 miles —the highest yet chronicled. Lockyer, moreover, has seen a prominence 40,000 miles high shattered in ten minutes; while uprushes have been witnessed by Respighi, of which the initial velocities were judged by him to be 400 or 500 miles a second. When it is remembered that a body starting from the sun's surface at the rate of 383 miles a second would, if it encountered no resistance, escape for ever from his control, it is obvious that we have, in the enormous forces of eruption or repulsion manifested in the outbursts just described, the means of accounting for the vast diffusion of matter in the solar neighbourhood. Nor is it possible to explain them away, as Cornu,[647] Faye,[648] and others have sought to do, by substituting for the rush of matter in motion, progressive illumination through electric discharges, chemical processes,[649] or even through the mere reheating of gases cooled by expansion.[650] All the appearances are against such evasions of the difficulty presented by velocities stigmatised as "fabulous" and "improbable," but which, there is the strongest reason to believe, really exist.

On the 12th of December, 1878, Sir Norman Lockyer formally expounded before the Royal Society his hypothesis of the compound nature of the "chemical elements."[651] An hypothesis, it is true, over and over again propounded from the simply terrestrial point of view. What was novel was the supra-terrestrial evidence adduced in its support; and even this had been, in a general and speculative way, anticipated by Professor F. W. Clarke of Washington.[652] Lockyer had been led to his conclusion along several converging lines of research. In a letter to M. Dumas, dated December 3, 1873, he had sketched out the successive stages of "celestial dissociation" which he conceived to be represented in the sun and stars. The absence from the solar spectrum of metalloidal absorption he explained by the separation, in the fierce solar furnace, of such substances as oxygen, nitrogen, sulphur, and chlorine, into simpler constituents possessing unknown spectra; while metals were at that time still admitted to be capable of existing there in a state of integrity. Three years later he shifted his position onward. He announced, as the result of a comparative study of the Fraunhofer and electric-arc spectra of calcium, that the "molecular grouping" of that metal, which at low temperatures gives a spectrum with its chief line in the blue, is nearly broken up in the sun into another or others with lines in the violet.[653] This came to be regarded by him as "a truly typical case."[654]

During four years (1875-78 inclusive) this diligent observer was engaged in mapping a section of the more refrangible part of the solar spectrum (wave-lengths 3,800-4,000) on a scale of magnitude such that, if completed down to the infra-red, its length would have been about *half a furlong*. The attendant laborious investigation, by the aid of photography, of metallic spectra, seemed to indicate the existence of what he called "basic lines." These held their ground persistently in the spectra of two or more metals after all possible "impurities" had been eliminated, and were therefore held to attest the presence of a common substratum of matter in a simpler state of aggregation than any with which we are ordinarily acquainted.

Later inquiries have shown, however, that between the spectral lines of different substances there are probably no *absolute* coincidences. "Basic" lines are really formed of doublets or triplets merged together by insufficient dispersion. Of Thalèn's original list of seventy rays common to several spectra,[655] very few resisted Thollon's and Young's powerful spectroscopes; and the process of resolution was completed by Rowland. Thus the argument from community of lines to community of substance has virtually collapsed. It was replaced by one founded on certain periodical changes on the spectra of sun-spots. They emerged from a series of observations begun at South Kensington under Sir Norman Lockyer's direction in 1879, and continued for fifteen years.[656]

The principle of the method employed is this. The whole range of Fraunhofer lines is visible when the light from a spot is examined with the spectroscope; but relatively few are widened. Now these widened lines alone constitute (presumably) the true spot-spectrum; they, and they alone, tell what kinds of vapour are thrust down into the strange dusky pit of the nucleus, the unaffected lines taking their accustomed origin from the overlying strata of the normal solar atmosphere. Here then we have the criterion that was wanted—the means of distinguishing, spectroscopically and chemically, between the cavity and the absorbing layers piled up above it. By its persistent employment some marked peculiarities have been brought out, such as the unfamiliar character of numerous lines in spot-spectra, especially at epochs of disturbance; and the strange *individuality* in the behaviour of every one of these darkened and distended rays. Each seems to act on its own account; it comports itself as if it were the sole representative of the substance emitting it; its appearance is unconditioned by that of any of its terrestrial companions in the same spectrum.

The most curious fact, however, elicited by these inquiries was that of the attendance of chemical vicissitudes upon the advance of the sun-spot period. As the maximum approached, unknown replaced known components of the spot-spectra in a most pronounced and unmistakable way.[657] It seemed as if the vapours emitting lines of iron, titanium, nickel, etc., had ceased to exist as such, and their room been taken by others, total strangers in terrestrial laboratories. These were held by Lockyer to be simply the finer constituents of their predecessors, dissociation having been effected by the higher temperature ensuing upon increased solar activity. But Father Cortie's supplementary investigations at Stonyhurst[658] modified, while they in the main substantiated, the South

Kensington results. They showed that the substitution of unknown for known lines characterizes disturbed spots, at all stages of the solar cycle, so that no systematic course of chemical change can be said to affect the sun as a whole. They showed further[659]—from evidence independent of that obtained by Young in 1892[660]—the remarkable conspicuousness in spot-spectra of vanadium lines excessively faint in the Fraunhofer spectrum. Lockyer's "unknown lines" may probably thus be accounted for. They represent absorption, not by new, but by scarce elements, especially, Father Cortie thinks, those with atomic weights of about 50. The circumstance of their development in solar commotions, largely to the exclusion of iron, is none the less curious; but it cannot be explained by any process of dissociation.

The theory has, however, to be considered under still another aspect. It frequently happens that the contortions or displacements due to motion are seen to affect a single line belonging to a particular substance, while the other lines of *that same substance* remain imperturbable. Now, how is this most singular fact, which seems at first sight to imply that a body may be at rest and in motion at one and the same instant, to be accounted for? It is accounted for, on the present hypothesis, easily enough, by supposing that the rays thus discrepant in their testimony, do *not* belong to one kind of matter, but to several, combined at ordinary temperatures to form a body in appearance "elementary." Of these different vapours, one or more may of course be rushing rapidly towards or from the observer, while the others remain still; and since the line of sight across the average prominence-region penetrates, at the sun's edge, a depth of about 300,000 miles,[661] all the incandescent materials separately occurring along which line are projected into a single "flame" or "cloud," it will be perceived that there is ample room for diversities of behaviour.

The alternative mode of escape from the perplexity consists in assuming that the vapour in motion is rendered luminous under conditions which reduce its spectrum to a few rays, the unaffected lines being derived from a totally distinct mass of the same substance shining with its ordinary emissions.[662] Thus, calcium can be rendered virtually monochromatic by attenuation, and analogous cases are not rare.

Sir Norman Lockyer only asks us to believe that effects which follow certain causes on the earth are carried a stage further in the sun, where the same causes must be vastly intensified. We find that the bodies we call "compound" split asunder at fixed degrees of heat *within* the range of our resources. Why should we hesitate to admit that the bodies we call "simple" do likewise at degrees of heat *without* the range of our resources? The term "element" simply expresses terrestrial incapability of reduction. That, in celestial laboratories, the means and their effect here absent should be present, would be an inference challenging, in itself, no expression of incredulity.

There are indeed theoretical objections to it which, though probably not insuperable, are unquestionably grave. Our seventy chemical "elements," for instance, are placed by the law of specific heats on a separate footing from their known compounds. We are not, it is true, compelled by it to believe their atoms to be really and absolutely such—to contain, that is, the "irreducible minimum" of material substance; but we do certainly gather from it that they are composed on a different principle from the salts and oxides made and unmade at pleasure by chemists. Then the multiplication of the species of matter with which Lockyer's results menace us, is at first sight startling. They may lead, we are told, to eventual unification, but the prospect appears remote. Their only obvious outcome is the disruption into several constituents of each terrestrial "element." The components of iron alone should be counted by the dozen. And there are other metals, such as cerium, which, giving a still more complex spectrum, would doubtless be still more numerously resolved. Sir Norman Lockyer interprets the observed phenomena as indicating the successive combinations, in varying proportions, of a very few original ingredients;[663] but no definite sign of their existence is perceptible; "protyle" seems likely long to evade recognition; and the only intelligible underlying principle for the reasonings employed—that of "one line, one element"—implies a throng beyond counting of formative material units.

Thus, added complexity is substituted for that fundamental unity of matter which has long formed the dream of speculators. And it is extremely remarkable that Sir William Crookes, working along totally different lines, has been led to analogous conclusions. To take only one example. As the outcome of extremely delicate operations of sifting and testing carried on for years, he finds that the metal yttrium splits up into five, if not eight constituents.[664] Evidently, old notions are doomed, nor are any preconceived ones likely to take their place. It would seem, on the contrary, as if their complete reconstruction were at hand. Subversive facts are steadily accumulating; the revolutionary ideas springing from them tend, if we interpret them aright, towards the substitution of electrical for chemical theories of matter. Dissociation by the brute force of heat is already nearly superseded, in the thoughts of physicists, by the more delicate process of "ionisation." Precisely what this implies and involves we do not know; but the symptoms of its occurrence are probably altogether different from those gathered by Sir Norman Lockyer from the collation of celestial spectra.

A. J. Ångström of Upsala takes rank after Kirchhoff as a subordinate founder, so to speak, of solar spectroscopy. His great map of the "normal" solar spectrum[665] was published in 1868, two years before he died. Robert Thalèn was his coadjutor in its execution, and the immense labour which it cost was amply repaid by its eminent and lasting usefulness. For more than a score of years it held its ground as the universal standard of reference in all spectroscopic inquiries within the range of the *visible* emanations. Those that are invisible by reason of the quickness of their vibrations were mapped by Dr. Henry Draper, of New York, in 1873, and with superior accuracy by M. Cornu in 1881. The infra-red part of the spectrum, investigated by Langley, Abney, and Knut Ångström, reaches perhaps no definite end. The radiations oscillating too slowly to affect the eye as light may pass by insensible gradations into the long Hertzian waves of electricity.[666]

Professor Rowland's photographic map of the solar spectrum, published in 1886, and in a second enlarged edition in 1889, opened fresh possibilities for its study, from far down in the red to high up in the ultra-violet, and the accompanying scale of absolute wave-lengths[667] has been, with trifling modifications, universally adopted. His new table of standard solar lines was published in 1893.[668] Through his work, indeed, knowledge of the solar spectrum so far outstripped knowledge of terrestrial spectra, that the recognition of their common constituents was hampered by intolerable uncertainties. Thousands of the solar lines charted with minute precision remained unidentified for want of a corresponding precision in the registration of metallic lines. Rowland himself, however, undertook to provide a remedy. Aided by Lewis E. Jewell, he redetermined, at the Johns Hopkins University, the wave-lengths of about 16,000 solar lines,[669] photographing for comparison with them the spectra of all the known chemical elements except gallium, of which he could procure no specimen. The labour of collation was well advanced when he died at the age of fifty-two, April 16, 1901. Investigations of metallic arc-spectra have also been carried out with signal success by Hasselberg,[670] Kayser and Runge, O. Lohse,[671] and others.

Another condition *sine quâ non* of progress in this department is the separation of true solar lines from those produced by absorption in our own atmosphere. And here little remains to be done. Thollon's great Atlas[672] was designed for this purpose of discrimination. Each of its thirty-three maps exhibits in quadruplicate a subdivision of the solar spectrum under varied conditions of weather and zenith-distance. Telluric effects are thus made easily legible, and they account wholly for 866, partly for 246, out of a total of 3,200 lines. But the death of the artist, April 8, 1887, unfortunately interrupted the half-finished task of the last seven years of his life. A most satisfactory record, meanwhile, of selective atmospheric action has been supplied by the experiments and determinations of Janssen, Cornu and Egoroff, by Dr. Becker's drawings,[673] and Mr. McClean's photographs of the analysed light of the sun at high, low, and medium altitudes; and the autographic pictures obtained by Mr. George Higgs, of Liverpool, of certain rhythmical groups in the red, emerging with surprising strength near sunset, excite general and well-deserved admiration.[674] The main interest, however, of all these documents resides in the information afforded by them regarding the chemistry of the sun.

The discovery that hydrogen exists in the atmosphere of the sun was made by Ångström in 1862. His list of solar elements published in that year,[675] the result of an investigation separate from, though conducted on the same principle as Kirchhoff's, included the substance which we now know to be predominant among them. Dr. Plücker of Bonn had identified in 1859 the Fraunhofer line F with the green ray of hydrogen, but drew no inference from his observation. The agreement was verified by Ångström; two further coincidences were established; and in 1866 a fourth hydrogen line in the extreme violet (named *h*) was detected in the solar spectrum. With Thalèn, he besides added manganese, titanium, and cobalt to the constituents of the sun enumerated by Kirchhoff, and raised the number of identical rays in the solar and terrestrial spectra of iron to no less than 460.[676]

Thus, when Sir Norman Lockyer entered on that branch of inquiry in 1872, fourteen substances were recognised as common to the earth and sun. Early in 1878 he was able to increase the list provisionally to thirty-three,[677] all except hydrogen metals. This rapid success was due to his adoption of the test of *length* in lieu of that of *strength* in the comparison of lines. He measured their relative significance, in other words, rather by their persistence through a wide range of temperature, than by their brilliancy at any one temperature. The distinction was easily drawn. Photographs of the electric arc, in which any given metal had been volatilised, showed some of the rays emitted by it stretching across the axis of the light to a considerable distance on either side, while many others clung more or less closely to its central hottest core. The former "long lines," regarded as certainly representative, were those primarily sought in the solar spectrum; while the attendant "short lines," often, in point of fact, due to foreign admixtures, were set aside as likely to be misleading.[678] The criterion is a valuable one, and its employment has greatly helped to quicken the progress of solar chemistry.

Carbon was the first non-metallic element discovered in the sun. Messrs. Trowbridge and Hutchins of Harvard College concluded in 1887,[679] on the ground of certain spectral coincidences, that this protean substance is vaporised in the solar atmosphere at a temperature approximately that of the voltaic arc. Partial evidence to the same effect had earlier been alleged by Lockyer, as well as by Liveing and Dewar; and the case was rendered tolerably complete by photographs taken by Kayser and Runge in 1889.[680] It was by Professor Rowland shown to be irresistible. Two hundred carbon-lines were, through his comparisons, sifted out from sunlight, and it contains others significant of the presence of silicon—a related substance, and one as important to rock-building on the earth, as carbon is to the maintenance of life. The general result of Rowland's labours was the establishment among solar materials, not only of these two out of the fourteen metalloids, or non-metallic substances, but of thirty-three metals, including silver and tin. Gold, mercury, bismuth, antimony, and arsenic were discarded from the catalogue; platinum and uranium, with six other metals, remained doubtful; while iron was recorded as crowding the spectrum with over two thousand obscure rays.[681] Gallium-absorption was detected in it by Hartley and Ramage in 1889.[682]

Dr. Henry Draper[683] announced, in 1877, his imagined discovery, in the solar spectrum, of eighteen especially brilliant spaces corresponding to oxygen-emissions. But the agreement proved, when put to the test of very high dispersion, to be wholly illusory.[684] Nor has it yet been found possible to identify, in analysed sunlight, any significant *bright* beams.[685]

The book of solar chemistry must be read in characters exclusively of absorption.

Nevertheless, the whole truth is unlikely to be written there. That a substance displays none of its distinctive beams in the spectrum of the sun or of a star, affords scarcely a presumption against its presence. For it may be situated below the level where absorption occurs, or under a pressure such as to efface lines by widening and weakening them; it may be at a temperature so high that it gives out more light than it takes up, and yet its incandescence may be masked by the absorption of other bodies; finally, it may just balance absorption by emission, with the result of complete spectral neutrality. An instructive example is that of the chromospheric element helium. Father Secchi remarked in 1868[686] that there is no dark line in the solar spectrum matching its light; and his observation has been fully confirmed.[687] Helium-absorption is, however, occasionally noticed in the penumbræ of spots.[688]

Our terrestrial vital element might then easily subsist unrecognisably in the sun. The inner organisation of the oxygen molecule is a considerably *plastic* one. It is readily modified by heat, and these modifications are reflected in its varying modes of radiating light. Dr. Schuster enumerated in 1879[689] four distinct oxygen spectra, corresponding to various stages of temperature, or phases of electrical excitement; and a fifth has been added by M. Egoroff's discovery in 1883[690] that certain well-known groups of dark lines in the red end of the solar spectrum (Fraunhofer's A and B) are due to absorption by the cool oxygen of our air. These persist down to the lowest temperatures, and even survive a change of state. They are produced essentially the same by liquid, as by aërial oxygen.[691]

It seemed, however, possible to M. Janssen that these bands owned a joint solar and terrestrial origin. Oxygen in a fit condition to produce them might, he considered, exist in the outer atmosphere of the sun; and he resolved to decide the point. No one could bring more skill and experience to bear upon it than he.[692] By observations on the summit of the Faulhorn, as well as by direct experiment, he demonstrated, nearly thirty years ago, the leading part played by water-vapour in generating the atmospheric spectrum; and he had recourse to similar means for appraising the share in it assignable to oxygen. An electric beam, transmitted from the Eiffel Tower to Meudon in the summer of 1888, having passed through a weight of oxygen about equal to that piled above the surface of the earth, showed the groups A and B just as they appear in the high-sun spectrum.[693] Atmospheric action is then adequate to produce them. But M. Janssen desired to prove, in addition, that they diminish proportionately to its amount. His ascent of Mont Blanc[694] in 1890 was undertaken with this object. It was perfectly successful. In the solar spectrum, examined from that eminence, oxygen-absorption was so much enfeebled as to leave no possible doubt of its purely telluric origin. Under another form, nevertheless, it has been detected as indubitably solar. A triplet of dark lines low down in the red, photographed from the sun by Higgs and McClean, was clearly identified by Runge and Paschen in 1896[695] with the fundamental group of an oxygen series, first seen by Piazzi Smyth in the spectrum of a vacuum-tube in 1883.[696] The *pabulum vitæ* of our earth is then to some slight extent effective in arresting transmitted sunlight, and oxygen must be classed as a solar element.

The rays of the sun, besides being stopped selectively in our atmosphere, suffer also a marked general absorption. This tells chiefly upon the shortest wave-lengths; the ultra-violet spectrum is in fact closed, as if by the interposition of an opaque screen. Nor does the screen appear very sensibly less opaque from an elevation of 10,000 feet. Dr. Simony's spectral photographs, taken on the Peak of Teneriffe,[697] extended but slightly further up than M. Cornu's, taken in the valley of the Loire. Could the veil be withdrawn, some indications as to the originating temperature of the solar spectrum might be gathered from its range, since the proportion of quick vibrations given out by a glowing body grows with the intensity of its incandescence. And this brings us to the subject of our next Chapter.

FOOTNOTES:

[596] *Phil. Mag.*, vol. xlii., p. 380, 1871.

[597] *Astr. Nach.*, No. 3,053, *Amer. Jour.*, vol. xlii., p. 162; Deslandres, *Comptes Rendus*, t. cxiii., p. 307.

[598] *Proc. Roy. Society*, vol. lxi., p. 433.

[599] *Phil. Mag.*, vol. xlii., p. 377.

[600] Frost-Scheiner, *Astr. Spectroscopy*, pp. 184, 423.

[601] *Proc. Roy. Soc.*, vol. xvii., p. 302.

[602] *Astr. Nach.*, No. 1,769.

[603] *Am. Jour. of Science*, vol. xv., p. 85.

[604] *Journ. Franklin Institute*, vol. xl., p. 232*a*.

[605] *Pogg. Annalen*, Bd. cxlvi., p. 475; *Astr. Nach.*, No. 3,014.

[606] *Astr. Nach.*, Nos. 3,006, 3,037.

[607] This device was suggested by Janssen in 1869.

[608] *Astr. and Astrophysics*, vol. xi., pp. 70, 407.

[609] *Astr. and Astrophysics*, vol. xi., p. 604.

[610] *Comptes Rendus*, t. cxiii., p. 307.

[611] *Astr. and Astrophysics*, vol. xi., p. 50.

[612] *Ibid.*, pp. 60, 314.

[613] Wiedemann's *Annalen der Physik*, Bd. xxv., p. 80.

[614] Evershed, *Knowledge*, vol. xxi., p. 133.

[615] Secchi, *Le Soleil*, t. ii., p. 294.

[616] Lockyer, *Chemistry of the Sun*, p. 418.

[617] *L'Astronomie*, August, 1884, p. 292 (Riccò); see also Evershed, *Jour. British Astr. Ass.*, vol. ii., p. 174.

[618] Averaging about 100 miles across and 300 high. *Le Soleil*, t. ii., p. 35.

[619] *The Sun*, p. 192.

[620] *Astr. Nach.*, No. 1,854.

[621] *Mem. degli Spettroscopisti Italiani*, t. v., p. 4; Secchi, *ibid.*, t. vi., p. 56.

[622] Its non-atmospheric character was early defined by Proctor, *Month. Not.*, vol. xxxi., p. 196.

[623] *Astroph. Jour.*, vol. vi., p. 412.

[624] *Ibid.*, vol. xi., p. 165.

[625] *Ibid.*, p. 243.

[626] *Sun's Place in Nature*, pp. 111, 288.

[627] *Abh. d. Kön. Böhm Ges. d. Wiss.*, Bd. ii., 1841-42, p. 467.

[628] In a paper read before the Société Philomathique de Paris, December 23, 1848, and first published *in extenso* in *Ann. de Chim. et de Phys.*, t. xix., p. 211 (1870). Hippolyte Fizeau died in September, 1896.

[629] *Astr. Nach.*, No. 1,772.

[630] *Ibid.*, No. 1,864.

[631] A. Cornu, *Sur la Méthode Doppler-Fizeau*, p. D. 23.

[632] *Am. Jour. of Sc.*, vol. xii., p. 321.

[633] *Ibid.*, vol. xiv., p. 140.

[634] *Bull. Astronom.*, February, 1884, p. 77.

[635] *Comptes Rendus*, t. xci., p. 368.

[636] *Month. Not.*, vol. xliv., p. 170.

[637] See *ante*, p. 147.

[638] *Recherches sur la Rotation du Soleil*, Upsal, 1891.

[639] Harzer, *Astr. Nach.*, No. 3,026; Stratonoff, *Ibid.*, No. 3,344.

[640] *Publ. Astr. Pacific Soc.*, vol. ii., p. 193.

[641] *Proc. Roy. Society*, vols. xvii., p. 415; xviii., p. 120.

[642] *Comptes Rendus*, t. cxii., p. 1421; t. cxiii., p. 310.

[643] At the sun's distance, one second of arc represents about 450 miles.

[644] *Amer. Jour. of Sc.*, vol. ii., p. 468, 1871.

[645] *Month. Not.*, vol. xxxii., p. 51.

[646] *Nature*, vol. xxiii., p. 281.

[647] *Comptes Rendus*, t. lxxxvii., p. 532.

[648] *Ibid.*, t. xcvi., p. 359.

[649] A. Brester, *Théorie du Soleil*, p. 66.

[650] Such prominences as have been seen to grow by the spread of incandescence are of the quiescent kind, and present no deceptive appearance of violent motion.

[651] *Proc. Roy. Soc.*, vol. xxviii., p. 157.

[652] "Evolution and the Spectroscope," *Pop. Science Monthly*, January, 1873.

[653] *Proc. Roy. Soc.*, vol. xxiv., p. 353. These are the H and K of prominences. H. W. Vogel discovered in 1879 a hydrogen-line nearly coincident with H (*Monatsb. Preuss. Ak.*, February, 1879, p. 118).

[654] *Proc. Roy. Soc.*, vol. xxviii., p. 444.

[655] Many of these were referred by Lockyer himself, who first sifted the matter, to traces of the metals concerned.

[656] *Chemistry of the Sun*, p. 312; *Proc. Roy. Society*, vol. lvii., p. 199.

[657] *Lockyer's Chemistry of the Sun*, p. 324.

[658] *Month. Not.*, vol. li., p. 76.

[659] *Ibid.*, vol. lviii., p. 370.

[660] *Astr. and Astrophysics*, vol. xi., p. 615.

[661] Thollon's estimate (*Comptes Rendus*, t. xcvii., p. 902) of 300,000 *kilometres*, seems considerably too low. Limiting the "average prominence region" to a shell 54,000 miles deep (2′ of arc as seen from the earth), the visual line will, at mid-height (27,000 miles from the sun's surface), travel through (in round numbers) 320,000 miles of that region.

[662] Liveing and Dewar, *Phil. Mag.*, vol. xvi. (5th ser.), p. 407.

[663] *Chemistry of the Sun*, p. 260.

[664] *Nature*, October 14, 1886.

[665] The normal spectrum is that depending exclusively upon wave-length—the fundamental constant given by nature as regards light. It is obtained by the interference of rays, in the manner first exemplified by Fraunhofer, and affords the only unvarying standard for measurement. In the refraction spectrum (upon which Kirchhoff's map was founded), the relative positions of the lines vary with the material of the prisms.

[666] Scheiner, *Die Spectralanalyse der Gestirne*, p. 168.

[667] *Phil. Mag.*, vol. xxvii., p. 479.

[668] *Astr. and Astrophysics*, vol. xii., p. 321; Frost-Scheiner, *Astr. Spectr.*, p. 363.

[669] Published in *Astroph. Jour.*, vols. i. to vi.

[670] *Astr. and Astrophysics*, vol. xi., p. 793.

[671] *Astroph. Jour.*, vol. vi., p. 95.

[672] *Annales de l'Observatoire de Nice*, t. iii., 1890.

[673] *Trans. Royal Society of Edinburgh*, vol. xxxvi., p. 99.

[674] Rev. A. L. Cortie, *Astr. and Astrophysics*, vol. xi., p. 401. Specimens of his photographs were given by Ranyard in *Knowledge*, vol. xiii., p. 212.

[675] *Ann. d. Phys.*, Bd. cxvii., p. 296.

[676] *Comptes Rendus*, t. lxiii., p. 647.

[677] *Ibid.*, t. lxxxvi., p. 317. Some half dozen of these identifications have proved fallacious.

[678] *Chemistry of the Sun*, p. 143.

[679] *Amer. Jour. of Science*, vol. xxxiv., p. 348.

[680] *Berlin Abhandlungen*, 1889.

[681] *Amer. Jour. of Science*, vol. xli., p. 243. See Appendix, Table II.

[682] *Astrophy. Jour.*, vol. ix., p. 219; Fowler, *Knowledge*, vol. xxiii., p. 11.

[683] *Amer. Jour, of Science*, vol. xiv., p. 89; *Nature*, vol. xvi., p. 364; *Month. Not.*, vol. xxxix., p. 440.

[684] *Month. Not.*, vol. xxxviii., p. 473; Trowbridge and Hutchins, *Amer. Jour. of Science*, vol. xxxiv., p. 263.

[685] Scheiner, *Die Spectralanalyse*, p. 180.

[686] *Comptes Rendus*, t. lxvii., p. 1123.

[687] Rev. A. L. Cortie, *Month. Not.*, vol. li., p. 18.

[688] Young, *The Sun*, p. 135; Hale, *Astr. and Astrophysics*, vol. xi., p. 312 Buss, *Jour. Brit. Astr. Ass.*, vol. ix., p. 253.

[689] *Phil. Trans.*, vol. clxx., p. 46.

[690] *Comptes Rendus*, t. xcvii., p. 555; t. ci., p. 1145.

[691] Liveing and Dewar, *Astr. and Astrophysics*, vol. xi., p. 705.

[692] *Comptes Rendus*, t. lx., p. 213; t. lxiii., p. 289.

[693] *Ibid.*, t. cviii., p. 1035.

[694] *Ibid.*, t. cxi., p. 431.

[695] *Astroph. Jour.*, vols. iv., p. 317; vi., p. 426.

[696] *Trans. Roy. Soc. Edin.*, vol. xxxii., p. 452.

[697] *Comptes Rendus*, t. cxi., p. 941; Huggins, *Proc. Roy. Soc.*, vol. xlvi., p. 168.

CHAPTER V

TEMPERATURE OF THE SUN

Newton was the first who attempted to measure the quantity of heat received by the earth from the sun. His object in making the experiment was to ascertain the temperature encountered by the comet of 1680 at its passage through perihelion. He found it, by multiplying the observed heating effects of direct sunshine according to the familiar rule of the “inverse squares of the distances,” to be about 2,000 times that of red-hot iron.[698]

Determinations of the sun’s thermal power, made with some scientific exactness, date, however, from 1837. A few days previous to the beginning of that year, Herschel began observing at the Cape of Good Hope with an “actinometer,” and obtained results agreeing quite satisfactorily with those derived by Pouillet from experiments made in France some months later with a “pyrheliometer.”[699] Pouillet found that the vertical rays of the sun falling on each square centimetre of the earth’s surface are competent (apart from atmospheric absorption) to raise the temperature of 1·7633 grammes of water one degree Centigrade per minute. This number (1·7633) he called the “solar constant”; and the unit of heat chosen is known as the “calorie.” Hence it was computed that the total amount of solar heat received during a year would suffice to melt a layer of ice covering the entire earth to a depth of 30·89 metres, or 100 feet; while the heat emitted would melt, at the sun’s surface, a stratum 11·80 metres thick each minute. A careful series of observations showed that nearly half the heat incident upon our atmosphere is stopped in its passage through it.

Herschel got somewhat larger figures, though he assigned only a third as the spoil of the air. Taking a mean between his own and Pouillet’s, he calculated that the ordinary expenditure of the sun per minute would have power to melt a cylinder of ice 184 feet in diameter, reaching from his surface to that of α Centauri; or, putting it otherwise, that an ice-rod 45·3 miles across, continually darted into the sun with the velocity of light, would scarcely consume, in dissolving, the thermal supplies now poured abroad into space.[700] It is nearly certain that this estimate should be increased by about two-thirds in order to bring it up to the truth.

Nothing would, at first sight, appear simpler than to pass from a knowledge of solar emission—a strictly measurable quantity—to a knowledge of the solar temperature; this being defined as the temperature to which a surface thickly coated with lamp-black (that is, of standard radiating power) should be raised to enable it to send us, from the sun’s distance, the amount of heat actually received from the sun. Sir John Herschel showed that heat-rays at the sun’s surface must be 92,000 times as dense as when they reach the earth; but it by no means follows that either the surface emitting, or a body absorbing those heat-rays must be 92,000 times hotter than a body exposed here to the full power of the sun.

The reason is, that the rate of emission—consequently the rate of absorption, which is its correlative—increases very much faster than the temperature. In other words, a body radiates or cools at a continually accelerated pace as it becomes more and more intensely heated above its surroundings.

Newton, however, took it for granted that radiation and temperature advance *pari passu*—that you have only to ascertain the quantity of heat received from, and the distance of a remote body in order to know how hot it is.[701] And the validity of this principle, known as "Newton's Law" of cooling, was never questioned until De la Roche pointed out, in 1812,[702] that it was approximately true only over a low range of temperature; while five years later, Dulong and Petit generalised experimental results into the rule, that while temperature grows by arithmetical, radiation increases by geometrical progression.[703] Adopting this formula, Pouillet derived from his observations on solar heat a solar temperature of somewhere between 1,461° and 1,761° C. Now, the higher of these points—which is nearly that of melting platinum—is undoubtedly surpassed at the focus of certain burning-glasses which have been constructed of such power as virtually to bring objects placed there within a quarter of a million of miles of the photosphere. In the rays thus concentrated, platinum and diamond become rapidly vaporised, notwithstanding the great loss of heat by absorption, first in passing through the air, and again in traversing the lens. Pouillet's maximum is then manifestly too low, since it involves the absurdity of supposing a radiating mass capable of heating a distant body more than it is itself heated.

Less demonstrably, but scarcely less surely, Mr. J. J. Waterston, who attacked the problem in 1860, erred in the opposite direction. Working up, on Newton's principle, data collected by himself in India and at Edinburgh, he got for the "potential temperature" of the sun 12,880,000° Fahr.,[704] equivalent to 7,156,000° C. The phrase *potential temperature* (for which Violle substituted, in 1876, *effective temperature*) was designed to express the accumulation in a single surface, postulated for the sake of simplicity, of the radiations not improbably received from a multitude of separate solar layers reinforcing each other; and might thus (it was explained) be considerably higher than the *actual* temperature of any one stratum.

At Rome, in 1861, Father Secchi repeated Waterston's experiments, and reaffirmed his conclusion;[705] while Soret's observations, made on the summit of Mont Blanc in 1867,[706] furnished him with materials for a fresh and even higher estimate of ten million degrees Centigrade.[707] Yet from the very same data, substituting Dulong and Petit's for Newton's law, Vicaire deduced in 1872 a *provisional* solar temperature of 1,398°.[708] This is below that at which iron melts, and we know that iron-vapour exists high up in the sun's atmosphere. The matter was taken into consideration on the other side of the Atlantic by Ericsson in 1871. He attempted to re-establish the shaken credit of Newton's principle, and arrived, by its means, at a temperature of 4,000,000° Fahrenheit.[709] Subsequently, an "underrated computation," based upon observation of the quantity of heat received by his "sun motor," gave him 3,000,000°. And the result, as he insisted, followed inevitably from the principle that the temperature produced by radiant heat is proportional to its density, or inversely as its diffusion.[710] The principle, however, is demonstrably unsound.

In 1876 the sun's temperature was proposed as the subject of a prize by the Paris Academy of Sciences; but although the essay of M. Jules Violle was crowned, the problem was declared to remain unsolved. Violle (who adhered to Dulong and Petit's formula) arrived at an *effective* temperature of 1,500° C., but considered that it might *actually* reach 2,500° C., if the emissive power of the photospheric clouds fell far short (as seemed probable) of the lamp-black standard.[711] Experiments made in April and May, 1881, giving a somewhat higher result, he raised this figure to 3,000° C.[712]

Appraisements so outrageously discordant as those of Waterston, Secchi, and Ericsson on the one hand, and those of the French *savants* on the other, served only to show that all were based upon a vicious principle. Professor F. Rosetti,[713] accordingly, of the Paduan University, at last perceived the necessity for getting out of the groove of "laws" plainly in contradiction with facts. The temperature, for instance, of the oxy-hydrogen flame was fixed by Bunsen at 2,800° C.—an estimate certainly not very far from the truth. But if the two systems of measurement applied to the sun be used to determine the heat of a solid body rendered incandescent in this flame, it comes out, by Newton's mode of calculation, 45,000° C.; by Dulong and Petit's, 870° C.[714] Both, then, are justly discarded, the first as convicted of exaggeration, the second of undervaluation. The formula substituted by Rosetti in 1878 was tested successfully up to 2,000° C.; but since, like its predecessors, it was a purely empirical rule, guaranteed by no principle, and hence not to be trusted out of sight, it was, like them, liable to break down at still higher elevations. Radiation by this new prescription increases as the *square* of the *absolute* temperature—that is, of the number of degrees counted from the "absolute zero" of -273° C. Its employment gave for the sun's radiating surface an effective temperature of 20,380° C. (including a supposed loss of one-half in the solar atmosphere); and setting a probable deficiency in emission (as compared with lamp-black) against a probable mutual reinforcement of superposed strata, Professor Rosetti considered "effective" as nearly equivalent to "actual" temperature. A "law of cooling," proposed by M. Stefan at Vienna in 1879,[715] was shown by Boltzmann, many years later, to have a certain theoretical validity.[716] It is that emission grows as the fourth power of absolute temperature. Hence the temperature of the photosphere would be proportional to the square root of the square root of its heating effects at a distance, and appeared, by Stefan's calculations from Violle's measures of solar radiative intensity, to be just 6,000° C.; while M. H. Le Chatelier[717] derived 7,600° from a formula, conveying an intricate and unaccountable relation between the temperature of an incandescent body and the intensity of its red radiations.

From a series of experiments carefully conducted at Daramona, Ireland, with a delicate thermal balance, of the kind invented by Boys and designated a "radio-micrometer," Messrs. Wilson and Gray arrived in 1893, with the aid of Stefan's Law, at a photospheric temperature of 7,400° C.,[718] reduced by the first-named investigator in 1901 to 6,590°.[719] Dr. Paschen, of Hanover, on the other hand, ascribed to the sun a temperature of 5,000° from comparisons between solar radiative intensity and that of glowing platinum;[720] while F. W. Very showed in 1895[721] that a minimum value of 20,000° C. for the same datum resulted from Paschen's formula connecting temperature with the position of maximum spectral energy.

A new line of inquiry was struck out by Zöllner in 1870. Instead of tracking the solar radiations backward with the dubious guide of empirical formulæ, he investigated their intensity at their source. He showed[722] that, taking prominences to be simple effects of the escape of powerfully compressed gases, it was possible, from the known mechanical laws of heat and gaseous constitution, to deduce minimum values for the temperatures prevailing in the area of their development. These came out 27,700° C. for the strata lying immediately above, and 68,400° C. for the strata lying immediately below the photosphere, the former being regarded as the region *into* which, and the latter as the region *from* which the eruptions took place. In this calculation, no prominences exceeding 40,000 miles (1·5′) in height were included. But in 1884, G. A. Hirn of Colmar, having regard to the enormous velocities of projection observed in the interim, fixed two million degrees Centigrade as the lowest *internal* temperature by which they could be accounted for; although admitting the photospheric condensations to be incompatible with a higher *external* temperature than 50,000° to 100,000° C.[723]

This method of going straight to the sun itself, observing what goes on there, and inferring conditions, has much to recommend it; but its profitable use demands knowledge we are still very far from possessing. We are quite ignorant, for instance, of the actual circumstances attending the birth of the solar flames. The assumption that they are nothing but phenomena of elasticity is a purely gratuitous one. Spectroscopic indications, again, give hope of eventually affording a fixed point of comparison with terrestrial heat sources; but their interpretation is still beset with uncertainties; nor can, indeed, the expression of transcendental temperatures in degrees of impossible thermometers be, at the best, other than a futile attempt to convey notions respecting a state of things altogether outside the range of our experience.

A more tangible, as well as a less disputable proof of solar radiative intensity than any mere estimates of temperature, was provided in some experiments made by Professor Langley in 1878.[724] Using means of unquestioned validity, he found the sun's disc to radiate 87 times as much heat, and 5,300 times as much light as an equal area of metal in a Bessemer converter after the air-blast had continued about twenty minutes. The brilliancy of the incandescent steel, nevertheless, was so blinding, that melted iron, flowing in a dazzling white-hot stream into the crucible, showed "deep brown by comparison, presenting a contrast like that of dark coffee poured into a white cup." Its temperature was estimated (not quite securely)[725] at about 2,000° C.; and no allowances were made, in computing relative intensities, for atmospheric ravages on sunlight, for the extra impediments to its passage presented by the smoke-laden air of Pittsburgh, or for the obliquity of its incidence. Thus, a very large balance of advantage lay on the side of the metal.

A further element of uncertainty in estimating the intrinsic strength of the sun's rays has still to be considered. From the time that his disc first began to be studied with the telescope, it was perceived to be less brilliant near the edges. Lucas Valerius, of the Lyncean Academy, seems to have been the first to note this fact, which, strangely enough, was denied by Galileo in a letter to Prince Cesi of January 25, 1613.[726] Father Scheiner, however, fully admitted it, and devoted some columns of his bulky tome to the attempt to find its appropriate explanation.[727] In 1729 Bouguer measured, with much accuracy, the amount of this darkening; and from his data, Laplace, adopting a principle of emission now known to be erroneous, concluded that the sun loses eleven-twelfths of his light through absorption in his own atmosphere.[728] The real existence of this atmosphere, which is totally distinct from the beds of ignited vapours producing the Fraunhofer lines, is not open to doubt, although its nature is still a matter of conjecture. The separate effects of its action on luminous, thermal, and chemical rays were carefully studied by Father Secchi, who in 1870[729] inferred the total absorption to be 88/100 of all radiations taken together, and added the important observation that the light from the limb is no longer white, but reddish-brown. Absorptive effects were thus seen to be unequally distributed; and they could evidently be studied to advantage only by taking the various rays of the spectrum separately, and finding out how much each had suffered in transmission.

This was done by H. C. Vogel in 1877.[730] Using a polarising photometer, he found that only 13 per cent. of the violet rays escape at the edge of the solar disc, 16 of the blue and green, 25 of the yellow, and 30 per cent. of the red. Midway between centre and limb, 88·7 of violet light and 96·7 of red penetrate the absorbing envelope, the abolition of which would increase the intensity of the sun's visible spectrum above two and a half times in the most, and once and a half times in the least refrangible parts. The nucleus of a small spot was ascertained to be of the same luminous intensity as a portion of the unbroken surface about two and a half minutes from the limb. These experiments having been made during a spot-minimum when there is reason to think that absorption is below its average strength, Vogel suggested their repetition at a time of greater activity. They were extended to the heat-rays by Edwin B. Frost. Detailed inquiries made at Potsdam in 1892[731] went to show that, were the sun's atmosphere removed, his thermal power, as regards ourselves, would be increased 1·7 times. They established, too, the practical uniformity in radiation of all parts of his disc. A confirmatory result was obtained about the same time by Wilson and Rambaut, who found that the unveiled sun would be once and a half times hotter than the actual sun.[732]

Professor Langley, now of Washington, gave to measures of the kind a refinement previously undreamt of. Reliable determinations of the "energy" of the individual spectral rays were, for the first time, rendered possible by his invention of the "bolometer" in 1880.[733] This exquisitely sensitive instrument affords the means of measuring heat, not directly, like the thermopile, but in its effects upon the conduction of electricity. It represents, in the phrase of the inventor, the finger laid upon the throttle-valve of a steam-engine. A minute force becomes the modulator of a much greater force, and thus from imperceptible becomes conspicuous. By locally raising the temperature of an inconceivably fine strip of platinum serving as the conducting-wire in a circuit, the flow of electricity is impeded at that point, and the included galvanometer records a disturbance of the electrical flow. Amounts of heat were thus detected in less than ten seconds, which, expended during a thousand years on the melting of a kilogramme of ice, would leave a part of the work still undone; and further improvements rendered this marvellous instrument capable of thrilling to changes of temperature falling short of one ten-millionth of a degree Centigrade.[734]

The heat contained in the diffraction spectrum is, with equal dispersions, barely one-tenth of that in the prismatic spectrum. It had, accordingly, never previously been found possible to measure it in detail—that is, ray by ray. But it is only from the diffraction, or normal spectrum that any true idea can be gained as to the real distribution of energy among the various constituents, visible and invisible, of a sunbeam. The effect of passage through a prism is to crowd together the red rays very much more than the blue. To this prismatic distortion was owing the establishment of a pseudo-maximum of heat in the infra-red, which disappeared when the natural arrangement by wave-length was allowed free play. Langley's bolometer has shown that the hottest part of the normal spectrum virtually coincides with its most luminous part, both lying in the orange, close to the D-line.[735] Thus the last shred of evidence in favour of the threefold division of solar radiations vanished, and it became obvious that the varying effects—thermal, luminous, or chemical—produced by them are due, not to any distinction of quality in themselves, but to the different properties of the substances they impinge upon. They are simply bearers of energy, conveyed in shorter or longer vibrations; the result in each separate case depending upon the capacity of the material particles meeting them for taking up those shorter or longer vibrations, and turning them variously to account in their inner economy.

A long series of experiments at Allegheny was completed in the summer of 1881 on the crest of Mount Whitney in the Sierra Nevada. Here, at an elevation of 14,887 feet, in the driest and purest air, perhaps, in the world, atmospheric absorptive inroads become less sensible, and the indications of the bolometer, consequently, surer and stronger. An enormous expansion was at once given to the invisible region in the solar spectrum below the red. Captain Abney had got chemical effects from undulations twelve ten-thousandths of a millimetre in length. These were the longest recognised as, or indeed believed, on theoretical grounds, to be capable of existing. Professor Langley now got heating effects from rays of above twice that wave-length, his delicate thread of platinum groping its way down nearly to thirty ten-thousandths of a millimetre, or three "microns." The known extent of the solar spectrum was thus at once more than doubled. Its visible portion covers a range of about one octave; bolometric indications already in 1884 comprised between three and four. The great importance of the newly explored region appears from the fact that three-fourths of the entire energy of sunlight reside in the infra-red, while scarcely more than one-hundredth part of that amount is found in the better known ultra-violet space.[736] These curious facts were reinforced, in 1886,[737] by further particulars learned with the help of rock-salt lenses and prisms, glass being impervious to very slow, as to very rapid vibrations. Traces were thus detected of solar heat distributed into bands of transmission alternating with bands of atmospheric absorption, far beyond the measurable limit of 5·3 microns.

In 1894, Langley described at the Oxford Meeting of the British Association[738] his new "bolographic" researches, in which the sensitive plate was substituted for the eye in recording deflections of the galvanometer responding to variations of invisible heat. Finally, in 1901,[739] he embodied in a splendid map of the infra-red spectrum 740 absorption-lines of determinate wave-lengths, ranging from 0·76 to 5·3 microns. Their chemical origin, indeed, remains almost entirely unknown, no extensive investigations having yet been undertaken of the slower vibrations distinctive of particular substances; but there is evidence that seven of the nine great bands crossing the "new spectrum" (as Langley calls it)[740] are telluric, and subject to seasonal change. Here, then, he thought, might eventually be found a sure standing-ground for vitally important previsions of famines, droughts, and bonanza-crops.

Atmospheric absorption had never before been studied with such precision as it was by Langley on Mount Whitney. Aided by simultaneous observations from Lone Pine, at the foot of the Sierra, he was able to calculate the intensity belonging to each ray before entering the earth's gaseous envelope—in other words, to construct an extra-atmospheric curve of energy in the spectrum. The result showed that the blue end suffered far more than the red, absorption varying inversely as wave-length. This property of stopping predominantly the quicker vibrations is shared, as both Vogel and Langley[741] have conclusively shown, by the solar atmosphere. The effect of this double absorption is as if two plates of reddish glass were interposed between us and the sun, the withdrawal of which would leave his orb, not only three or four times more brilliant, but in colour distinctly greenish-blue.[742]

The fact of the uncovered sun being *blue* has an important bearing upon the question of his temperature, to afford a somewhat more secure answer to which was the ultimate object of Professor Langley's persevering researches; for it is well known that as bodies grow hotter, the proportionate representation in their spectra of the more refrangible rays becomes greater. The lowest stage of incandescence is the familiar one of *red* heat. As it gains intensity, the quicker vibrations come in, and an optical balance of sensation is established at *white* heat. The final term of *blue* heat, as we now know, is attained by the photosphere. On this ground alone, then, of the large original preponderance of blue light, we must raise our estimate of solar heat; and actual measurements show the same upward tendency. Until quite lately, Pouillet's figure of 1.7 calories per minute per square centimetre of terrestrial surface, was the received value for the "solar constant." Forbes had, it is true, got 2.85 from observations on the Faulhorn in 1842;[743] but they failed to obtain the confidence they merited. Pouillet's result was not definitely superseded until Violle, from actinometrical measures at the summit and base of Mont Blanc in 1875, computed the intensity of solar radiation at 2.54,[744] and Crova, about the same time, at Montpellier, showed it to be above two calories.[745] Langley went higher still. Working out the results of the Mount Whitney expedition, he was led to conclude atmospheric absorption to be fully twice as effective as had hitherto been supposed. Scarcely 60 per cent., in fact, of those solar radiations which strike perpendicularly through a seemingly translucent sky, were estimated to attain the sea-level. The rest are reflected, dispersed, or absorbed. This discovery involved a large addition to the original supply so mercilessly cut down in transmission, and the solar constant rose at once to three calories. Nor did the rise stop there. M. Savélieff deduced for it a value of 3.47 from actinometrical observations made at Kieff in 1890;[746] and Knut Ångström, taking account of the arrestive power of carbonic acid, inferred enormous atmospheric absorption, and a solar constant of four calories.[747] In other words, the sun's heat reaching the outskirts of our atmosphere is capable of doing without cessation the work of an engine of four-horse power for each square yard of the earth's surface. Thus, modern inquiries tend to render more and more evident the vastness of the thermal stores contained in the great central reservoir of our system, while bringing into fair agreement the estimates of its probable temperature. This is in great measure due to the acquisition of a workable formula by which to connect temperature with radiation. Stefan's rule of a fourth-power relation, if not actually a law of nature, is a colourable imitation of one; and its employment has afforded a practical certainty that the sun's temperature, so far as it is definable, neither exceeds 12,000° C., nor falls short of 6,500° C.

FOOTNOTES:

[698] *Principia*, p. 498 (1st ed.).

[699] *Comptes Rendus*, t. vii., p. 24.

[700] *Results of Astr. Observations*, p. 446.

[701] "Est enim calor solis ut radiorum densitas, hoc est, reciproce ut quadratum distantiæ locorum a sole."—*Principia*, p. 508 (3d ed., 1726).

[702] *Jour. de Physique*, t. lxxv., p. 215.

[703] *Ann. de Chimie*, t. vii., 1817, p. 365.

[704] *Phil. Mag.*, vol. xxiii. (4th ser.), p. 505.

[705] *Nuovo Cimento*, t. xvi., p. 294.

[706] *Comptes Rendus*, t. lxv., p. 526.

[707] The direct result of 5-1/3 million degrees was doubled in allowance for absorption in the sun's own atmosphere. *Comptes Rendus*, t. lxxiv., p. 26.

[708] *Ibid.*, p. 31.

[709] *Nature*, vols. iv., p. 204; v., p. 505.

[710] *Ibid.*, vol. xxx., p. 467.

[711] *Ann. de Chim.*, t. x. (5th ser.), p. 361.

[712] *Comptes Rendus*, t. xcvi., p. 254.

[713] *Phil. Mag.*, vol. viii., p. 324, 1879.

[714] *Ibid.*, p. 325.

[715] *Sitzungsberichte*, Wien, Bd. lxxix., ii., p. 391.

[716] *Wiedemann's Annalen*, Bd. xxii., p. 291; *Scheiner, Strahlung und Temperatur der Sonne*, p. 27.

[717] *Comptes Rendus*, March 28, 1892; *Astr. and Astrophysics*, vol. xi., p. 517.

[718] *Phil. Trans.*, vol. clxxxv., p. 361.

[719] *Proc. Roy. Society*, December 12, 1901.

[720] Scheiner, *Temp. der Sonne*, p. 36.

[721] *Astroph. Jour.*, vol. ii., p. 318.

[722] *Astr. Nach.*, Nos. 1,815-16.

[723] *L'Astronomie*, September, 1884, p. 334.

[724] *Amer. Jour. of Science*, vol. i. (3rd ser.), p. 653.

[725] Young, *The Sun*, p. 310.

[726] *Op.*, t. vi., p. 198.

[727] *Rosa Ursina*, lib. iv., p. 618.

[728] *Méc. Cél.*, liv. x., p. 323.

[729] *Le Soleil* (1st ed.), p. 136.

[730] *Monatsber.*, Berlin, 1877, p. 104.

[731] *Astr. Nach.*, Nos. 3,105-6; *Astr. and Astrophysics*, vol. xi., p. 720.

[732] *Proc. Roy. Irish Acad.*, vol. ii., No. 2, 1892.

[733] *Am. Jour. of Sc.*, vol. xxi., p. 187.

[734] *Amer. Jour. of Science*, vol. v., p. 245, 1898.

[735] For J. W. Draper's partial anticipation of this result, see *Ibid.* vol. iv., 1872, p. 174.

[736] *Phil. Mag.*, vol. xiv., p. 179, 1883.

[737] "The Solar and the Lunar Spectrum," *Memoirs National Acad. of Science*, vol. xxxii.; "On hitherto Unrecognised Wave-lengths," *Amer. Jour. of Science*, vol. xxxii., August, 1886.

[738] *Astroph. Jour.*, vol. i., p. 162.

[739] *Annals of the Smithsonian Astroph. Observatory*, vol. i.; *Comptes Rendus*, t. cxxxi., p. 734; *Astroph. Jour.*, vol. iii., p. 63.

[740] *Phil. Mag.*, July, 1901.

[741] *Comptes Rendus*, t. xcii., p. 701.

[742] *Nature*, vol. xxvi., p. 589.

[743] *Phil. Trans.*, vol. cxxxii., p. 273.

[744] *Ann. de Chim.*, t. x., p. 321.

[745] *Ibid.*, t. xi., p. 505.

[746] *Comptes Rendus*, t. cxii., p. 1200.

[747] *Wied. Ann.*, Bd. xxxix., p. 294; Scheiner, *Temperatur der Sonne*, pp. 36, 38.

CHAPTER VI

THE SUN'S DISTANCE

The question of the sun's distance arises naturally from the consideration of his temperature, since the intensity of the radiations emitted as compared with those received and measured, depends upon it. But the knowledge of that distance has a value quite apart from its connection with solar physics. The semi-diameter of the earth's orbit is our standard measure for the universe. It is the great fundamental datum of astronomy—the unit of space, any error in the estimation of which is multiplied and repeated in a thousand different ways, both in the planetary and sidereal systems. Hence its determination was called by Airy "the noblest problem in astronomy." It is also one of the most difficult. The quantities dealt with are so minute that their sure grasp tasks all the resources of modern science. An observational inaccuracy which would set the moon nearer to, or farther from us than she really is by one hundred miles, would vitiate an estimate of the sun's distance to the extent of sixteen million![748] What is needed in order to attain knowledge of the desired exactness is no less than this: to measure an angle about equal to that subtended by a halfpenny 2,000 feet from the eye, within a little more than a thousandth part of its value.

The angle thus represented is what is called the "horizontal parallax" of the sun. By this amount—the breadth of a halfpenny at 2,000 feet—he is, to a spectator on the rotating earth, removed at rising and setting from his meridian place in the heavens. Such, in other terms, would be the magnitude of the terrestrial radius as viewed from the sun. If we knew this magnitude with certainty and precision, we should also know with certainty and precision—the dimensions of the earth being, as they are, well ascertained—the distance of the sun. In fact, the one quantity commonly stands for the other in works treating professedly of astronomy. But this angle of parallax or apparent displacement cannot be directly measured—cannot even be perceived with the finest instruments. Not from its smallness. The parallactic shift of the nearest of the stars as seen from opposite sides of the earth's orbit, is many times smaller. But at the sun's limb, and close to the horizon, where the visual angle in question opens out to its full extent, atmospheric troubles become overwhelming, and altogether swamp the far more minute effects of parallax.

There remain indirect methods. Astronomers are well acquainted with the proportions which the various planetary orbits bear to each other. They are so connected, in the manner expressed by Kepler's Third Law, that the periods being known, it only needs to find the interval between any two of them in order to infer at once the distances separating them all from one another and from the sun. The plan is given; what we want to discover is the scale upon which it is drawn; so that, if we can get a reliable measure of the distance of a single planet from the earth, our problem is solved.

Now some of our fellow-travellers in our unending journey round the sun, come at times well within the scope of celestial trigonometry. The orbit of Mars lies at one point not more than thirty-five million miles outside that of the earth, and when the two bodies happen to arrive together in or near the favourable spot—a conjuncture which occurs every fifteen years—the desired opportunity is granted. Mars is then "in opposition," or on the *opposite* side of us from the sun, crossing the meridian consequently at midnight.[749] It was from an opposition of Mars, observed in 1672 by Richer at Cayenne in concert with Cassini in Paris, that the first scientific estimate of the sun's distance was derived. It appeared to be nearly eighty-seven millions of miles (parallax 9·5′); while Flamsteed deduced 81,700,000 (parallax 10′) from his independent observations of the same occurrence—a difference quite insignificant at that stage of the inquiry. But Picard's result was just half Flamsteed's (parallax 20′; distance forty-one million miles); and Lahire considered that we must be separated from the hearth of our system by an interval of *at least* 136 million miles.[750] So that uncertainty continued to have an enormous range.

Venus, on the other hand, comes closest to the earth when she passes between it and the sun. At such times of "inferior conjunction" she is, however, still twenty-six million miles, or (in round numbers) 109 times as distant as the moon. Moreover, she is so immersed in the sun's rays that it is only when her path lies across his disc that the requisite facilities for measurement are afforded. These "partial eclipses of the sun by Venus" (as Encke termed them) are coupled together in pairs,[751] of which the components are separated by eight years, recurring at intervals alternately of 105-1/2 and 121-1/2 years. Thus, the first calculated transit took place in December, 1631, and its companion (observed by Horrocks) in the same month (N.S.), 1639. Then, after the lapse of 121-1/2 years, came the June couple of 1761 and 1769; and again after 105-1/2, the two last observed, December 8, 1874, and December 6, 1882. Throughout the twentieth century there will be no transit of Venus; but the astronomers of the twenty-first will only have to wait four years for the first of a June pair. The rarity of these events is due to the fact that the orbits of the earth and Venus do not lie in the same plane. If they did, there would be a transit each time that our twin-planet overtakes us in her more rapid circling—that is, on an average, every 584 days. As things are actually arranged, she passes above or below the sun, except when she happens to be very near the line of intersection of the two tracks.

Such an occurrence as a transit of Venus seems, at first sight, full of promise for solving the problem of the sun's distance. For nothing would appear easier than to determine exactly either the duration of the passage of a small, dark orb across a large brilliant disc, or the instant of its entry upon or exit from it. And the differences in these times (which, owing to the comparative nearness of Venus, are quite considerable), as observed from remote parts of the earth, can be translated into differences of space—that is, into apparent or parallactic displacements, whereby the distance of Venus becomes known, and thence, by a simple sum in proportion, the distance of the sun. But in that word "exactly" what snares and pitfalls lie hid! It is so easy to think and to say; so indefinitely hard to realise.

The astronomers of the eighteenth century were full of hope and zeal. They confidently expected to attain, through the double opportunity offered them, to something like a permanent settlement of the statistics of our system. They were grievously disappointed. The uncertainty as to the sun's distance, which they had counted upon reducing to a few hundred thousand miles, remained at many millions.

In 1822, however, Encke, then director of the Seeberg Observatory near Gotha, undertook to bring order out of the confusion of discordant, and discordantly interpreted observations. His combined result for both transits (1761 and 1769) was published in 1824,[752] and met universal acquiescence. The parallax of the sun thereby established was 8·5776′, corresponding to a mean distance[753] of 95-1/4 million miles. Yet this abolition of doubt was far from being so satisfactory as it seemed. Serenity on the point lasted exactly thirty years. It was disturbed in 1854 by Hansen's announcement[754] that the observed motions of the moon could be drawn into accord with theory only on the terms of bringing the sun considerably nearer to us than he was supposed to be.

Dr. Matthew Stewart, professor of mathematics in the University of Edinburgh, had made a futile attempt in 1763 to deduce the sun's distance from his disturbing power over our satellite.[755] Tobias Mayer of Göttingen, however, whose short career was fruitful of suggestions, struck out the right way to the same end; and Laplace, in the seventh book of the *Mécanique Céleste*,[756] gave a solar parallax derived from the lunar "parallactic inequality" substantially identical with that issuing from Encke's subsequent discussion of the eighteenth-century transits. Thus, two wholly independent methods—the trigonometrical, or method by survey, and the gravitational, or method by perturbation—seemed to corroborate each the upshot of the use of the other until the nineteenth century was well past its meridian. It is singular how often errors conspire to lead conviction astray.

Hansen's note of alarm in 1854 was echoed by Leverrier in 1858.[757] He found that an apparent monthly oscillation of the sun which reflects a real monthly movement of the earth round its common centre of gravity with the moon, and which depends for its amount solely on the mass of the moon and the distance of the sun, required a diminution in the admitted value of that distance by fully four million miles. Three years later he pointed out that certain perplexing discrepancies between the observed and computed places both of Venus and Mars, would vanish on the adoption of a similar measure.[758] Moreover, a favourable opposition of Mars gave the opportunity in 1862 for fresh observations, which, separately worked out by Stone and Winnecke, agreed with all the newer investigations in fixing the great unit at slightly over 91 million miles. In Newcomb's hands they gave 92-1/2 million.[759] The accumulating evidence in favour of a large reduction in the sun's distance was just then reinforced by an auxiliary result of a totally different and unexpected kind.

The discovery that light does not travel instantaneously from point to point, but takes some short time in transmission, was made by Olaus Römer in 1675, through observing that the eclipses of Jupiter's satellites invariably occurred later, when the earth was on the far side, than when it was on the near side of its orbit. Half the difference, or the time spent by a luminous vibration in crossing the "mean radius" of the earth's orbit, is called the "light-equation"; and the determination of its precise value has claimed the minute care distinctive of modern astronomy. Delambre in 1792 made it 493 seconds. Glasenapp, a Russian astronomer, raised the estimate in 1874 to 501, Professor Harkness adopts a safe medium value of 498 seconds. Hence, if we had any independent means of ascertaining how fast light travels, we could tell at once how far off the sun is.

There is yet another way by which knowledge of the swiftness of light would lead us straight to the goal. The heavenly bodies are perceived, when carefully watched and measured, to be pushed forward out of their true places, in the direction of the earth's motion, by a very minute quantity. This effect (already adverted to) has been known since Bradley's time as "aberration." It arises from a combination of the two movements of the earth round the sun and of the light-waves through the ether. If the earth stood still, or if light spent no time on the road from the stars, such an effect would not exist. Its amount represents the proportion between the velocities with which the earth and the light-rays pursue their respective journeys. This proportion is, roughly, one to ten thousand. So that here again, if we knew the rate per second of luminous transmission, we should also know the rate per second of the earth's movement, consequently the size of its orbit and the distance of the sun.

But, until lately, instead of finding the distance of the sun from the velocity of light, there has been no means of ascertaining the velocity of light except through the imperfect knowledge possessed as to the distance of the sun. The first successful terrestrial experiments on the point date from 1849; and it is certainly no slight triumph of human ingenuity to have taken rigorous account of the delay of a sunbeam in flashing from one mirror to another. Fizeau led the way,[760] and he was succeeded, after a few months, by Léon Foucault,[761] who, in 1862, had so far perfected Wheatstone's method of revolving mirrors, as to be able to announce with authority that light travelled slower, and that the sun was in consequence nearer than had been supposed.[762] Thus a third line of separate research was found to converge to the same point with the two others.

Such a conspiracy of proof was not to be resisted, and at the anniversary meeting of the Royal Astronomical Society in February, 1864, the correction of the solar distance took the foremost place in the annals of the year. Lest, however, a sudden bound of four million miles nearer to the centre of our system should shake public faith in astronomical accuracy, it was explained that the change in the solar parallax corresponding to that huge leap, amounted to no more than the breadth of a human hair 125 feet from the eye![763] The Nautical Almanac gave from 1870 the altered value of 8.95′, for which Newcomb's result of 8.85′, adopted in 1869 in the Berlin Ephemeris, was substituted some ten years later. In astronomical literature the change was initiated by Sir Edmund Beckett in the first edition (1865) of his *Astronomy without Mathematics*.

If any doubt remained as to the misleading character of Encke's deduction, so long implicitly trusted in, it was removed by Powalky's and Stone's rediscussions, in 1864 and 1868 respectively, of the transit observations of 1769. Using improved determinations of the longitude of the various stations, and a selective judgment in dealing with their materials, which, however indispensable, did not escape adverse criticism, they brought out results confirmatory of the no longer disputed necessity for largely increasing the solar parallax, and proportionately diminishing the solar distance. Once more in 1890, and this time with better success, the eighteenth-century transits were investigated by Professor Newcomb.[764] Turning to account the experience gained in the interim regarding the optical phenomena accompanying such events, he elicited from the mass of somewhat discordant observations at his command, a parallax (8·79′) in close agreement with the value given by sundry modes of recent research.

Conclusions on the subject, however, were still regarded as purely provisional. A transit of Venus was fast approaching, and to its arbitrament, as to that of a court of final appeal, the pending question was to be referred. It is true that the verdict in the same case by the same tribunal a century earlier had proved of so indecisive a character as to form only a starting-point for fresh litigation; but that century had not passed in vain, and it was confidently anticipated that observational difficulties, then equally unexpected and insuperable, would yield to the elaborate care and skill of forewarned modern preparation.

The conditions of the transit of December 8, 1874, were sketched out by Sir George Airy, then Astronomer-Royal, in 1857,[765] and formed the subject of eager discussion in this and other countries down to the very eve of the occurrence. In these Mr. Proctor took a leading part; and it was due to his urgent representations that provision was made for the employment of the method identified with the name of Halley,[766] which had been too hastily assumed inapplicable to the first of each transit-pair. It depends upon the difference in the length of time taken by the planet to cross the sun's disc, as seen from various points of the terrestrial surface, and requires, accordingly, the visibility of both entrance and exit at the same station. Since these were, in 1874, separated by about three and a half hours, and the interval may be much longer, the choice of posts for the successful use of the "method of durations" is a matter of some difficulty.

The system described by Delisle in 1760, on the other hand, involves merely noting the instant of ingress or egress (according to situation) from opposite extremities of a terrestrial diameter; the disparity in time giving a measure of the planet's apparent displacement, hence of its actual rate of travel in miles per minute, from which its distances severally from earth and sun are immediately deducible. Its chief attendant difficulty is the necessity for accurately fixing the longitudes of the points of observation. But this was much more sensibly felt a century ago than it is now, the improved facility and certainty of modern determinations tending to give the Delislean plan a decided superiority over its rival.

These two traditional methods were supplemented in 1874 by the camera and the heliometer. From photography, above all, much was expected. Observations made by its means would have the advantages of impartiality, multitude, and permanence. Peculiarities of vision and bias of judgment would be eliminated; the slow progress of the phenomenon would permit an indefinite number of pictures to be taken, their epochs fixed to a fraction of a second; while subsequent leisurely comparison and measurement could hardly fail, it was thought, to educe approximate truth from the mass of accumulated evidence. The use of the heliometer (much relied on by German observers) was so far similar to that of the camera that the object aimed at by both was the determination of the relative positions of the *centres* of the sun and Venus viewed, at the same absolute instant, from opposite sides of the globe. So that the principle of the two older methods was to ascertain the exact times of meeting between the solar and planetary limbs; that of the two modern to determine the position of the dark body already thrown into complete relief by its shining background. The former are “methods by contact,” the latter “methods by projection.”

Every country which had a reputation to keep or to gain for scientific zeal was forward to co-operate in the great cosmopolitan enterprise of the transit. France and Germany each sent out six expeditions; twenty-six stations were in Russian, twelve in English, eight in American, three in Italian, one in Dutch occupation. In all, at a cost of nearly a quarter of a million, some fourscore distinct posts of observation were provided; among them such inhospitable, and all but inaccessible rocks in the bleak Southern Ocean, as St. Paul’s and Campbell Islands, swept by hurricanes, and fitted only for the habitation of seabirds, where the daring votaries of science, in the wise prevision of a long leaguer by the elements, were supplied with stores for many months, or even a whole year. Siberia and the Sandwich Islands were thickly beset with observers; parties of three nationalities encamped within the mists of Kerguelen Island, expressively termed the “Land of Desolation,” in the sanguine, though not wholly frustrated hope of a glimpse of the sun at the right moment. M. Janssen narrowly escaped destruction from a typhoon in the China seas on his way to Nagasaki; Lord Lindsay (now Earl of Crawford and Balcarres) equipped, at his private expense, an expedition to Mauritius, which was in itself an epitome of modern resource and ingenuity.

During several years, the practical methods best suited to insure success for the impending enterprise formed a subject of European debate. Official commissions were appointed to receive and decide upon evidence; and experiments were in progress for the purpose of defining the actual circumstances of contacts, the precise determination of which constituted the only tried, though by no means an assuredly safe road to the end in view. In England, America, France, and Germany, artificial transits were mounted, and the members of the various expeditions were carefully trained to unanimity in estimating the phases of junction and separation between a moving dark circular body and a broad illuminated disc. In the previous century, a formidable and prevalent phenomenon, which acquired notoriety as the “Black Drop” or “Black Ligament,” had swamped all pretensions to rigid accuracy. It may be described as substituting adhesion for contact, the limbs of the sun and planet, instead of meeting and parting with the desirable clean definiteness, *clinging* together as if made of some glutinous material, and prolonging their connection by means of a dark band or dark threads stretched between them. Some astronomers ascribed this baffling appearance entirely to instrumental imperfections; others to atmospheric agitation; others again to the optical encroachment of light upon darkness known as “irradiation.” It is probable that all these causes conspired, in various measure, to produce it; and it is certain that its *conspicuous* appearance may, by suitable precautions, be obviated.

The organisation of the British forces reflected the utmost credit on the energy and ability of Lieutenant-Colonel Tupman, who was responsible for the whole. No useful measure was neglected. Each observer went out ticketed with his “personal equation,” his senses drilled into a species of martial discipline, his powers absorbed, so far as possible, in the action of a cosmopolitan observing machine. Instrumental uniformity and uniformity of method were obtainable, and were attained; but diversity of judgment unhappily survived the best-directed efforts for its extirpation.

The eventful day had no sooner passed than telegrams began to pour in, announcing an outcome of considerable, though not unqualified success. The weather had proved generally favourable; the manifold arrangements had worked well; contacts had been plentifully observed; photographs in lavish abundance had been secured; a store of materials, in short, had been laid up, of which it would take years to work out the full results by calculation. Gradually, nevertheless, it came to be known that the hope of a definitive issue must be abandoned. Unanimity was found to be as remote as ever. The dreaded “black ligament” gave, indeed, less trouble than was expected; but another appearance supervened which took most observers by surprise. This was the illumination due to the atmosphere of Venus. Astronomers, it is true, were not ignorant that the planet had, on previous occasions, been seen girdled with a lucid ring; but its power to mar observations by the distorting effect of refraction had scarcely been reckoned with. It proved, however, to be very great. Such was the difficulty of determining the critical instant of internal contact, that (in Colonel Tupman’s words) “observers side by side, with adequate optical means, differed as much as twenty or thirty seconds in the times they recorded for phenomena which they have described in almost identical language.”[767]

Such uncertainties in the data admitted of a corresponding variety in the results. From the British observations of ingress and egress Sir George Airy[768] derived, in 1877, a solar parallax of 8·76′ (corrected to 8·754′), indicating a mean distance of 93,375,000 miles. Mr. Stone obtained a value of ninety-two millions (parallax 8·88′), and held any parallax less than 8·84′ or more than 8·93′ to be “absolutely negatived” by the documents available.[769] Yet, from the same, Colonel Tupman deduced 8·81′,[770] implying a distance 700,000 miles greater than Stone had obtained. The best French observations of contacts gave a parallax of about 8·88′; French micrometric measures the obviously exaggerated one of 9·05′.[771]

Photography, as practised by most of the European parties, was a total failure. Utterly discrepant values of the microscopic displacements designed to serve as sounding lines for the solar system, issued from attempts to measure even the most promising pictures. “You might as well try to measure the zodiacal light,” it was remarked to Sir George Airy. Those taken on the American plan of using telescopes of so great focal length as to afford, without further enlargement, an image of the requisite size, gave notably better results. From an elaborate comparison of those dating from Vladivostock, Nagasaki, and Pekin, with others from Kerguelen and Chatham Islands, Professor D. P. Todd, of Amherst College, deduced a solar distance of about ninety-two million miles (parallax 8·883′ ±0·034′),[772] and the value was much favoured by concurrent evidence.

On the whole, estimates of the great spatial unit cannot be said to have gained any security from the combined effort of 1874. A few months before the transit, Mr. Proctor considered that the uncertainty then amounted to 1,448,000 miles;[773] five years after the transit, Professor Harkness judged it to be still 1,575,950 miles;[774] yet it had been hoped that it would have been brought down to 100,000. As regards the end for which it had been undertaken, the grand campaign had come to nothing. Nevertheless, no sign of discouragement was apparent. There was a change of view, but no relaxation of purpose. The problem, it was seen, could be solved by no single heroic effort, but by the patient approximation of gradual improvements. Astronomers, accordingly, looked round for fresh means or more refined expedients for applying those already known. A new phase of exertion was entered upon.

On September 5, 1877, Mars came into opposition near the part of his orbit which lies nearest to that of the earth, and Dr. Gill (now Sir David) took advantage of the circumstance to appeal once more to him for a decision on the *quæstio vexata* of the sun’s distance. He chose, as the scene of his labours, the Island of Ascension, and for their plan a method recommended by Airy in 1857,[775] but never before fairly tried. This is known as the “diurnal method of parallaxes.” Its principle consists in substituting successive morning and evening observations from the same spot, for simultaneous observations from remote spots, the rotation of the earth supplying the necessary difference in the points of view. Its great advantage is that of unity in performance. A single mind, looking through the same pair of eyes, reinforced with the same optical appliances, is employed throughout, and the errors inseparable from the combination of data collected under different conditions are avoided. There are many cases in which one man can do the work of two better than two men can do the work of one. The result of Gill’s skilful determinations (made with Lord Lindsay’s heliometer) was a solar parallax of 8·78′, corresponding to a distance of 93,080,000 miles.[776] The bestowal of the Royal Astronomical Society's gold medal stamped the merit of this distinguished service.

But there are other subjects for this kind of inquiry besides Mars and Venus. Professor Galle of Breslau suggested in 1872[777] that some of the minor planets might be got to repay astronomers for much disinterested toil spent in unravelling their motions, by lending aid to their efforts towards a correct celestial survey. Ten or twelve come near enough, and are bright enough for the purpose; in fact, the absence of sensible magnitude is one of their chief recommendations, since a point of light offers far greater facilities for exact measurement than a disc. The first attempt to work this new vein was made at the opposition of Phocæa in 1872; and from observations of Flora in the following year at twelve observatories in the northern and southern hemispheres, Galle deduced a solar parallax of 8·87′.[778] At Mauritius in 1874, Lord Lindsay and Sir David Gill applied the "diurnal method" to Juno, then conveniently situated for the purpose; and the continued use of similar occasions affords an unexceptionable means for improving knowledge of the sun's distance. They frequently recur; they need no elaborate preparation; a single astronomer armed with a heliometer can do all the requisite work. Dr. Gill, however, organized a more complex plan of operations upon Iris in 1888, and upon Victoria and Sappho in 1889. A novel method was adopted. Its object was to secure simultaneous observations made from opposite sides of the globe just when the planet lay in the plane passing through the centre of the earth and the two observers, the same pair of reference-stars being used on each occasion. The displacements caused by parallax were thus in a sense doubled, since the star to which the planet seemed approximated in the northern hemisphere, showed as if slightly removed from it in the southern, and *vice versâ*. As the planet pursued its course, fresh star-couples came into play, during the weeks that the favourable period lasted. In these determinations, only heliometers were employed. Dr. Elkin, of Yale college, co-operated throughout, and the heliometers of Dresden, Göttingen, Bamberg, and Leipzig, shared in the work, while Dr. Auwers of Berlin was Sir David Gill's personal coadjutor at the Cape. Voluminous data were collected; meridian observations of the stars of reference for Victoria occupied twenty-one establishments during four months; the direct work of triangulation kept four heliometers in almost exclusive use for the best part of a year; and the ensuing toilsome computations, carried out during three years at the Cape Observatory, filled two bulky tomes[779] with their details. Gill's final result, published in 1897, was a parallax of 8·802′, equivalent to a solar distance of 92,874,000; and it was qualified by a probable error so small that the value might well have been accepted as definitive but for an unlooked-for discovery. The minor planet Eros, detected August 14, 1898, was found to pursue a course rendering it an almost ideal intermediary in solar parallax-determinations. Once in thirty years, it comes within fifteen million miles of the earth; and although the next of these choice epochs must be awaited for some decades, an opposition too favourable to be neglected occurred in 1900. At an International Conference, accordingly, held at Paris in July of that year, a plan of photographic operations was concerted between the representatives of no less than 58 observatories.[780] Its primary object was to secure a large stock of negatives showing the planet with the comparison-stars along the route traversed by it from October, 1900, to March, 1901,[781] and this at least was successfully attained. Their measurement will in due time educe the apparent displacements of the moving object as viewed simultaneously from remote parts of the earth; and the upshot should be a solar parallax adequate in accuracy to the exigent demands of the twentieth century.

The second of the nineteenth-century pair of Venus-transits was looked forward to with much abated enthusiasm. Russia refused her active co-operation in observing it, on the ground that oppositions of the minor planets were trigonometrically more useful, and financially far less costly; and her example was followed by Austria; while Italian astronomers limited their sphere of action to their own peninsula. Nevertheless, it was generally held that a phenomenon which the world could not again witness until it was four generations older should, at the price of any effort, not be allowed to pass in neglect.

The persuasion of its importance justified the summoning of an International Conference at Paris in 1881, from which, however, America, preferring independent action, held aloof. It was decided to give Delisle's method another trial; and the ambiguities attending and marring its use were sought to be obviated by careful regulations for insuring agreement in the estimation of the critical moments of ingress and egress.[782] But in fact (as M. Puiseux had shown[783]), contacts between the limbs of the sun and planet, so far from possessing the geometrical simplicity attributed to them, are really made up of a prolonged succession of various and varying phases, impossible either to predict or identify with anything like rigid exactitude. Sir Robert Ball compared the task of determining the precise instant of their meeting or parting, to that of telling the hour with accuracy on a watch without a minute hand; and the comparison is admittedly inadequate. For not only is the apparent movement of Venus across the sun extremely slow, being but the excess of her real motion over that of the earth; but three distinct atmospheres—the solar, terrestrial, and Cytherean—combine to deform outlines and mask the geometrical relations which it is desired to connect with a strict count of time.

The result was very much what had been expected. The arrangements were excellent, and were only in a few cases disconcerted by bad weather. The British parties, under the experienced guidance of Mr. Stone, the late Radcliffe observer, took up positions scattered over the globe, from Queensland to Bermuda; the Americans collected a whole library of photographs; the Germans and Belgians trusted to the heliometer; the French used the camera as an adjunct to the method of contacts. Yet little or no approach was made to solving the problem. Thus, from 606 measures of Venus on the sun, taken with a new kind of heliometer at Santiago in Chili, M. Houzeau, of the Brussels Observatory, derived a solar parallax of 8.907′, and a distance of 91,727,000 miles.[784] But the "probable errors" of this determination amounted to 0.084′ either way: it was subject to a "more or less" of

900,000, or to a total uncertainty of 1,800,000 miles. The "probable error" of the English result, published in 1887, was less formidable,[785] yet the details of the discussion showed that no great confidence could be placed in it. The sun's distance came out 92,560,000 miles; while 92,360,000 was given by Professor Harkness's investigation of 1,475 American photographs.[786] Finally, Dr. Auwers deduced from the German heliometric measures the unsatisfactorily small value of 92,000,000 miles.[787] The transit of 1882 had not, then, brought about the desired unanimity.

The state and progress of knowledge on this important topic were summed up by Faye and Harkness in 1881.[788] The methods employed in its investigation fall (as we have seen) into three separate classes—the trigonometrical, the gravitational, and the "phototachymetrical"—an ungainly adjective used to describe the method by the velocity of light. Each has its special difficulties and sources of error; each has counter-balancing advantages. The only trustworthy result from celestial surveys, was at that time furnished by Gill's observations of Mars in 1877. But the method by lunar and planetary disturbances is unlike all the others in having time on its side. It is this which Leverrier declared with emphasis must inevitably prevail, because its accuracy is continually growing.[789] The scarcely perceptible errors which still impede its application are of such a nature as to accumulate year by year; eventually, then, they will challenge, and must receive, a more and more perfect correction. The light-velocity method, however, claimed, and for some years justified, M. Faye's preference.

By a beautiful series of experiments on Foucault's principle, Michelson fixed in 1879 the rate of luminous transmission at 299,930 (corrected later to 299,910) kilometres a second.[790] This determination was held by Professor Todd to be entitled to four times as much confidence as any previous one; and if the solar parallax of 8·758′ deduced from it by Professor Harkness errs somewhat by defect, it is doubtless because Glasenapp's "light-equation," with which it was combined, errs slightly by excess. But all earlier efforts of the kind were thrown into the shade by Professor Newcomb's arduous operations at Washington in 1880-1882.[791] The scale upon which they were conducted was in itself impressive. Foucault's entire apparatus in 1862 had been enclosed in a single room; Newcomb's revolving and fixed mirrors, between which the rays of light were to run their timed course, were set up on opposite shores of the Potomac, at a distance of nearly four kilometres. This advantage was turned to the utmost account by ingenuity and skill in contrivance and execution; and the deduced velocity of 299,860 kilometres = 186,328 miles a second, had an estimated error (30 kilometres) only one-tenth that ascribed by Cornu to his own result in 1874.

Just as these experiments were concluded in 1882, M. Magnus Nyrén, of St. Petersburg, published an elaborate investigation of the small annular displacements of the stars due to the successive transmission of light, involving an increase of Struve's "constant of aberration" from 20·445′ to 20·492′. And from the new value, combined with Newcomb's light-velocity, was derived a valuable approximation to the sun's distance, concluded at 92,905,021 miles (parallax = 8·794′). Yet it is not quite certain that Nyrén's correction was an improvement. A differential method of determining the amount of aberration, struck out by M. Loewy of Paris,[792] avoids most of the objections to the absolute method previously in vogue; and the upshot of its application in 1891 was to show that Struve's constant might better be retained than altered, Loewy's of 20·447′ varying from it only to an insignificant extent. Professor Hall had, moreover, deduced nearly the same value (20·454′) from the Washington observations since 1862, of α Lyræ (Vega); whence, in conjunction with Newcomb's rate of light transmission, he arrived at a solar parallax of 8·81′.[793] Inverting the process, Sir David Gill in 1897 derived the constant from the parallax. If the earth's orbit have a mean radius, as found by him, of 92,874,000 miles, then, he calculated, the aberration of light—Newcomb's measures of its velocity being supposed exact—amounts to 20.467′. This figure can need very slight correction.

Professor Harkness surveyed in 1891,[794] from an eclectic point of view, the general situation as regarded the sun's parallax. Convinced that no single method deserved an exclusive preference, he reached a plausible result through the combination, on the principle of least squares—that is, by the mathematical rules of probability—of all the various quantities upon which the great datum depends. It thus summed up and harmonised the whole of the multifarious evidence bearing upon the point, and, as modified in 1894,[795] falls very satisfactorily into line with the Cape determination. We may, then, at least provisionally, accept 92,870,000 miles as the length of our measuring-rod for space. Nor do we hazard much in fixing 100,000 miles as the outside limit of its future correction.

FOOTNOTES:

[748] Airy, *Month. Not.*, vol. xvii., p. 210.

[749] Mars comes into opposition once in about 780 days; but owing to the eccentricity of both orbits, his distance from the earth at those epochs varies from thirty-five to sixty-two million miles.

[750] J. D. Cassini, *Hist. Abrégée de la Parallaxe du Soleil*, p. 122, 1772.

[751] The present period of coupled eccentric transits will, in the course of ages, be succeeded by a period of single, nearly central transits. The alignments by which transits are produced, of the earth, Venus, and the sun, close to the place of intersection of the two planetary orbits, now occur, the first a little in front of, the second, after eight years less two and a half days, a little behind the node. But when the first of these two meetings takes place very near the node, giving a nearly central transit, the second falls too far from it, and the planet escapes projection on the sun. The reason of the liability to an eight-yearly recurrence is that eight revolutions of the earth are accomplished in only a very little more time than thirteen revolutions of Venus.

[752] *Die Entfernung der Sonne: Fortsetzung*, p. 108. Encke slightly corrected his results of 1824 in *Berlin Abh.*, 1835, p. 295.

[753] Owing to the ellipticity of its orbit, the earth is nearer to the sun in January than in June by 3,100,000 miles. The quantity to be determined, or "mean distance," is that lying midway between these extremes—is, in other words, half the major axis of the ellipse in which the earth travels.

[754] *Month. Not.*, vol. xv., p. 9.

[755] *The Distance of the Sun from the Earth determined by the Theory of Gravity*, Edinburgh, 1763.

[756] *Opera*, t. iii., p. 326.

[757] *Comptes Rendus*, t. xlvi., p. 882. The parallax 8·95′ derived by Leverrier from the above-described inequality in the earth's motion, was corrected by Stone to 8·91′. *Month. Not.*, vol. xxviii., p. 25.

[758] *Month. Not.*, vol. xxxv., p. 156.

[759] *Wash. Obs.*, 1865, App. ii., p. 28.

[760] *Comptes Rendus*, t. xxix., p. 90.

[761] *Ibid.*, t. xxx., p. 551.

[762] *Ibid.*, t. lv., p. 501. The previously admitted velocity was 308 million metres per second; Foucault reduced it to 298 million. Combined with Struve's "constant of aberration" this gave 8.86′ for the solar parallax, which exactly agreed with Cornu's result from a repetition of Fizeau's experiments in 1872. *Comptes Rendus*, t. lxxvi., p. 338.

[763] *Month. Not.*, vol. xxiv., p. 103.

[764] *Astr. Papers of the American Ephemeris*, vol. ii., p. 263.

[765] *Month. Not.*, vol. xvii., p. 208.

[766] Because closely similar to that proposed by him in *Phil. Trans.* for 1716.

[767] *Month. Not.*, vol. xxxviii., p. 447.

[768] *Ibid.*, p. 11.

[769] *Ibid.*, p. 294.

[770] *Ibid.*, p. 334.

[771] *Comptes Rendus*, t. xcii., p. 812.

[772] *Observatory*, vol. v., p. 205.

[773] *Transits of Venus*, p. 89 (1st ed.).

[774] *Am. Jour. of Sc.*, vol. xx., p. 393.

[775] *Month. Not.*, vol. xvii., p. 219.

[776] *Mem. Roy. Astr. Soc.*, vol. xlvi., p. 163.

[777] *Astr. Nach.*, No. 1,897.

[778] Hilfiker, *Bern Mittheilungen*, 1878, p. 109.

[779] *Annals of the Cape Observatory*, vols. vi., vii.

[780] *Rapport sur l'État de l'Observatoire de Paris pour l'Année 1900*, p. 7.

[781] *Observatory*, vol. xxiii., p. 311; Newcomb, *Astr. Jour.*, No. 480.

[782] *Comptes Rendus*, t. xciii., p. 569.

[783] *Ibid.*, t. xcii., p. 481.

[784] *Bull. de l'Acad.*, t. vi., p. 842.

[785] *Month. Not.*, vol. xlviii., p. 201.

[786] *Astr. Jour.*, No. 182.

[787] *Astr. Nach.*, No. 3,066.

[788] *Comptes Rendus*, t. xcii., p. 375; *Am. Jour. of Sc.*, vol. xxii., p. 375.

[789] *Month. Not.*, vol. xxxv., p. 401.

[790] *Am. Jour. of Sc.*, vol. xviii., p. 393.

[791] *Nature*, vol. xxxiv., p. 170; *Astron. Papers of the American Ephemeris*, vol. ii., p. 113.

[792] *Comptes Rendus*, t. cxii., p. 549.

[793] *Astr. Journ.*, Nos. 169, 170

[794] *The Solar Parallax and its Related Constants*, Washington, 1891.

[795] *Astr. and Astrophysics*, vol. xiii., p. 626.

CHAPTER VII

PLANETS AND SATELLITES

Johann Hieronymus Schröter was the Herschel of Germany. He did not, it is true, possess the more brilliant gifts of his rival. Herschel’s piercing discernment, comprehensive intelligence, and inventive splendour were wanting to him. He was, nevertheless, the founder of descriptive astronomy in Germany, as Herschel was in England.

Born at Erfurt in 1745, he prosecuted legal studies at Göttingen, and there imbibed from Kästner a life-long devotion to science. From the law, however, he got the means of living, and, what was to the full as precious to him, the means of observing. Entering the sphere of Hanoverian officialism in 1788, he settled a few years later at Lilienthal, near Bremen, as “Oberamtmann,” or chief magistrate. Here he built a small observatory, enriched in 1785 with a seven-foot reflector by Herschel, then one of the most powerful instruments to be found anywhere out of England. It was soon surpassed, through his exertions, by the first-fruits of native industry in that branch. Schrader of Kiel transferred his workshops to Lilienthal in 1792, and constructed there, under the superintendence and at the cost of the astronomical Oberamtmann, a thirteen-foot reflector, declared by Lalande to be the finest telescope in existence, and one twenty-seven feet in focal length, probably as inferior to its predecessor in real efficiency as it was superior in size.

Thus, with instruments of gradually increasing power, Schröter studied during thirty-four years the topography of the moon and planets. The field was then almost untrodden; he had but few and casual predecessors, and has since had no equal in the sustained and concentrated patience of his hourly watchings. Both their prolixity and their enthusiasm are faithfully reflected in his various treatises. Yet the one may be pardoned for the sake of the other, especially when it is remembered that he struck out a substantially new line, and that one of the main lines of future advance. Moreover, his infectious zeal communicated itself; he set the example of observing when there was scarcely an observer in Germany; and under his roof Harding and Bessel received their training as practical astronomers.

But he was reserved to see evil days. Early in 1813 the French under Vandamme occupied Bremen. On the night of April 20, the Vale of Lilies was, by their wanton destructiveness, laid waste with fire; the Government offices were destroyed, and with them the chief part of Schröter’s property, including the whole stock of his books and writings. There was worse behind. A few days later, his observatory, which had escaped the conflagration, was broken into, pillaged, and ruined. His life was wrecked with it. He survived the catastrophe three years without the means to repair, or the power to forget it, and gradually sank from disappointment into decay, terminated by death, August 29, 1816. He had, indeed, done all the work he was capable of; and though not of the first quality, it was far from contemptible. He laid the foundation of the *comparative* study of the moon’s surface, and the descriptive particulars of the planets laboriously collected by him constituted a store of more or less reliable information hardly added to during the ensuing half century. They rested, it is true, under some shadow of doubt; but the most recent observations have tended on several points to rehabilitate the discredited authority of the Lilienthal astronomer. We may now briefly resume, and pursue in its further progress, the course of his studies, taking the planets in the order of their distances from the sun.

In April, 1792, Schröter saw reason to conclude, from the gradual degradation of light on its partially illuminated disc, that Mercury possesses a tolerably dense atmosphere.[796] During the transit of May 7, 1799, he was, moreover, struck with the appearance of a ring of softened luminosity encircling the planet to an apparent height of three seconds, or about a quarter of its own diameter.[797] Although a "mere thought" in texture, it remained persistently visible both with the seven-foot and the thirteen-foot reflectors, armed with powers up to 288. It had a well-marked grayish boundary, and reminded him, though indefinitely fainter, of the penumbra of a sun-spot. A similar appendage had been noticed by De Plantade at Montpellier, November 11, 1736, and again in 1786 and 1789 by Prosperin and Flaugergues; but Herschel, on November 9, 1802, saw the preceding limb of the planet projected on the sun cut the luminous solar clouds with the most perfect sharpness.[798] The presence, however, of a "halo" was unmistakable in 1832, when Professor Moll, of Utrecht, described it as a "nebulous ring of a darker tinge approaching to the violet colour."[799] Again, to Huggins and Stone, November 5, 1868, it showed as lucid and most distinct. No change in the colour of the glasses used, or the powers applied, could get rid of it, and it lasted throughout the transit.[800] It was next seen by Christie and Dunkin at Greenwich, May 6, 1878,[801] and with much precision of detail by Trouvelot at Cambridge (U.S.).[802] Professor Holden, on the other hand, noted at Hastings-on-Hudson the total absence of all anomalous appearances.[803] Nor could any vestige of them be perceived by Barnard at Lick on November 10, 1894.[804] Various effects of irradiation and diffraction were, however, observed by Lowell and W. H. Pickering at Flagstaff;[805] and Davidson was favoured at San Francisco with glimpses of the historic aureola,[806] as well as of a central whitish spot, which often accompanies it. That both are somehow of optical production can scarcely be doubted.

Nothing can be learned from them regarding the planet's physical condition. Airy showed that refraction in a Mercurian atmosphere could not possibly originate the noted aureola, which must accordingly be set down as "strictly an ocular nervous phenomenon."[807] It is the less easy to escape from this conclusion that we find the virtually airless moon capable of exhibiting a like appendage. Professor Stephen Alexander, of the United States Survey, with two other observers, perceived, during the eclipse of the sun of July 18, 1860, the advancing lunar limb to be bordered with a bright band;[808] and photographic effects of the same kind appear in pictures of transits of Venus and partial solar eclipses.

The spectroscope affords little information as to the constitution of Mercury. Its light is of course that of the sun reflected, and its spectrum is consequently a faint echo of the Fraunhofer spectrum. Dr. H. C. Vogel, who first examined it in April, 1871, *suspected* traces of the action of an atmosphere like ours,[809] but, it would seem, on slight grounds. It is, however, certainly very poor in blue rays. More definite conclusions were, in 1874,[810] derived by Zöllner from photometric observations of Mercurian phases. A similar study of the waxing and waning moon had afforded him the curious discovery that light-changes dependent upon phase vary with the nature of the reflecting surface, following a totally different law on a smooth homogeneous globe and on a rugged and mountainous one. Now the phases of Mercury—so far as could be determined from only two sets of observations—correspond with the latter kind of structure. Strictly analogous to those of the moon, they seem to indicate an analogous mode of surface-formation. This conclusion was fully borne out by Müller's more extended observations at Potsdam during the years 1885-1893.[811] Practical assurance was gained from them that the innermost planet has a rough rind of dusky rock, absorbing all but 17 per cent. of the light poured upon it by the fierce adjacent sun. Its "albedo," in other words, is 0·17,[812] which is precisely that ascribed to the moon. The absence of any appreciable Mercurian atmosphere followed almost necessarily from these results.

On March 26, 1800, Schröter, observing with his 13-foot reflector in a peculiarly clear sky, perceived the southern horn of Mercury's crescent to be quite distinctly blunted.[813] Interception of sunlight by a Mercurian mountain rather more than eleven English miles high explained the effect to his satisfaction. By carefully timing its recurrence, he concluded rotation on an axis in a period of 24 hours 4 minutes. The first determination of the kind rewarded twenty years of unceasing vigilance. It received ostensible confirmation from the successive appearances of a dusky streak and blotch in May and June, 1801.[814] These, however, were inferred to be no permanent markings on the body of the planet, but atmospheric formations, the streak at times drifting forwards (it was thought) under the fluctuating influence of Mercurian breezes. From a rediscussion of these somewhat doubtful observations Bessel inferred that Mercury rotates on an axis inclined 70° to the plane of its orbit in 24 hours 53 seconds.

The rounded appearance of the southern horn seen by Schröter was more or less doubtfully caught by Noble (1864), Burton, and Franks (1877);[815] but was obvious to Mr. W. F. Denning at Bristol on the morning of November 5, 1882.[816] That the southern polar regions are usually less bright than the northern is well ascertained; but the cause of the deficiency remains dubious. If inequalities of surface are in question, they must be on a considerable scale; and a similar explanation might be given of the deformations of the "terminator"—or dividing-line between darkness and light in the planet's phases—first remarked by Schröter, and again clearly seen by Trouvelot in 1878 and 1881.[817] The displacement, during four days, of certain brilliant and dusky spaces on the disc indicated to Mr. Denning in 1882 rotation in about twenty-five hours; while the general aspect of the planet reminded him of that of Mars.[818] But the difficulties in the way of its observation are enormously enhanced by its constant close attendance on the sun.

In his sustained study of the features of Mercury, Schröter had no imitator until Schiaparelli took up the task at Milan in 1882. His observations were made in daylight. It was found that much more could be seen, and higher magnifying powers used, high up in the sky near the sun, than at low altitudes, through the agitated air of morning or evening twilight. A notable discovery ensued.[819] Following the planet hour by hour, instead of making necessarily brief inspections at intervals of about a day, as previous observers had done, it was found that the markings faintly visible remained sensibly fixed, hence, that there was no rotation in a period at all comparable with that of the earth. And after long and patient watching, the conclusion was at last reached that Mercury turns on his axis in the same time needed to complete a revolution in his orbit. One of his hemispheres, then, is always averted from the sun, as one of the moon's hemispheres from the earth, while the other never shifts from beneath his torrid rays. The "librations," however, of Mercury are on a larger scale than those of the moon, because he travels in a more eccentric path. The temporary inequalities arising between his "even pacing" on an axis and his alternately accelerated and retarded elliptical movement occasion, in fact, an oscillation to and fro of the boundaries of light and darkness on his globe over an arc of 47° 22′, in the course of his year of 88 days. Thus the regions of perpetual day and perpetual night are separated by two segments, amounting to one-fourth of the entire surface, where the sun rises and sets once in 88 days. Else there is no variation from the intense glare on one side of the globe, and the nocturnal blackness on the other.

To Schiaparelli's scrutiny, Mercury appeared as a "spotty globe," enveloped in a tolerably dense atmosphere. The brownish stripes and streaks, discerned on his rose-tinged disc, and judged to be permanent, were made the basis of a chart. They were not indeed always equally well seen. They disappeared regularly near the limb, and were at times veiled even when centrally situated. Some of them had been clearly perceived by De Ball at Bothkamp in 1882.[820]

Mr. Lowell followed Schiaparelli's example by observing Mercury in the full glare of noon. "The best time to study him," he remarked, "is when planetary almanacs state 'Mercury invisible.'" A remarkable series of drawings executed, some at Flagstaff in 1896, the remainder at Mexico in 1897, supplied grounds for the following, among other, conclusions.[821] Mercury rotates synchronously with its revolution—that is, once in 88 days—on an axis sensibly perpendicular to its orbital plane. No certain signs of a Mercurian atmosphere are visible. The globe is seamed and furrowed with long narrow markings, explicable as cracks in cooling. It is, and always was, a dead world. From micrometrical measures, moreover, the inferences were drawn that the planet's mass has a probable value about 1/20 that of the earth, while its mean density falls considerably short of the terrestrial standard.

The theory of Mercury's movements has always given trouble. In Lalande's,[822] as in

Mästlin's time, the planet seemed to exist for no other purpose than to throw discredit on astronomers; and even to Leverrier's powerful analysis it long proved recalcitrant. On the 12th of September, 1869, however, he was able to announce before the Academy of Sciences[823] the terms of a compromise between observation and calculation. They involved the addition of a new member to the solar system. The hitherto unrecognised presence of a body about the size of Mercury itself revolving at somewhat less than half its mean distance from the sun (or, if farther, then of less mass, and *vice versâ*), would, it was pointed out, produce exactly the effect required, of displacing the perihelion of the former planet 38′ a century more than could otherwise be accounted for. The planes of the two orbits, however, should not lie far apart, as otherwise a nodal disturbance would arise not perceived to exist. It was added that a ring of asteroids similarly placed would answer the purpose equally well, and was more likely to have escaped notice.

Upon the heels of this forecast followed promptly a seeming verification. Dr. Lescarbault, a physician residing at Orgères, whose slender opportunities had not blunted his hopes of achievement, had, ever since 1845, when he witnessed a transit of Mercury, cherished the idea that an unknown planet might be caught thus projected on the solar background. Unable to observe continuously until 1858, he, on March 26, 1859, saw what he had expected—a small perfectly round object slowly traversing the sun's disc. The fruitless expectation of reobserving the phenomenon, however, kept him silent, and it was not until December 22, after the news of Leverrier's prediction had reached him, that he wrote to acquaint him with his supposed discovery.[824] The Imperial Astronomer thereupon hurried down to Orgères, and by personal inspection of the simple apparatus used, by searching cross-examination and local inquiry, convinced himself of the genuine character and substantial accuracy of the reported observation. He named the new planet "Vulcan," and computed elements giving it a period of revolution slightly under twenty days.[825] But it has never since been seen. M. Liais, director of the Brazilian Coast Survey, thought himself justified in asserting that it never had been seen. Observing the sun for twelve minutes after the supposed ingress recorded at Orgères, he noted those particular regions of its surface as "très uniformes d'intensité."[826] He subsequently, however, admitted Lescarbault's good faith, at first rashly questioned. The planet-seeking doctor was, in truth, only one among many victims of similar illusions.

Waning interest in the subject was revived by a fresh announcement of a transit witnessed, it was asserted, by Weber at Peckeloh, April 4, 1876.[827] The pseudo-planet, indeed, was detected shortly afterwards on the Greenwich photographs, and was found to have been seen by M. Ventosa at Madrid in its true character of a sun-spot without penumbra; but Leverrier had meantime undertaken the investigation of a list of twenty similar dubious appearances, collected by Haase, and republished by Wolf in 1872.[828] From these, five were picked out as referring in all likelihood to the same body, the reality of whose existence was now confidently asserted, and of which more or less probable transits were fixed for March 22, 1877, and October 15, 1882.[829] But, widespread watchfulness notwithstanding, no suspicious object came into view at either epoch.

The next announcement of the discovery of “Vulcan” was on the occasion of the total solar eclipse of July 29, 1878.[830] This time it was stated to have been seen at some distance south-west of the obscured sun, as a ruddy star with a minute planetary disc; and its simultaneous detection by two observers—the late Professor James C. Watson, stationed at Rawlins (Wyoming Territory), and Professor Lewis Swift at Denver (Colorado)—was at first readily admitted. But their separate observations could, on a closer examination, by no possibility be brought into harmony, and, if valid, certainly referred to two distinct objects, if not to four; each astronomer eventually claiming a pair of planets. Nor could any one of the four be identified with Lescarbault’s and Leverrier’s Vulcan, which, if a substantial body revolving round the sun, must then have been found on the *east* side of that luminary.[831] The most feasible explanation of the puzzle seems to be that Watson and Swift merely saw each the same two stars in Cancer: haste and excitement doing the rest.[832] Nevertheless, they strenuously maintained their opposite conviction.[833]

Intra-Mercurian planets have since been diligently searched for when the opportunity of a total eclipse offered, especially during the long obscuration at Caroline Island. Not only did Professor Holden “sweep” in the solar vicinity, but Palisa and Trouvelot agreed to divide the field of exploration, and thus make sure of whatever planetary prey there might be within reach; yet with only negative results. Photographic explorations during recent eclipses have been equally fruitless. Belief in the presence of any considerable body or bodies within the orbit of Mercury is, accordingly, at a low ebb. Yet the existence of the anomaly in the Mercurian movements indicated by Leverrier has been made only surer by further research.[834] Its elucidation constitutes one of the “pending problems” of astronomy.

From the observation at Bologna in 1666-67 of some very faint spots, Domenico Cassini concluded a rotation or libration of Venus—he was not sure which—in about twenty-three hours.[835] By Bianchini in 1726 the period was augmented to twenty-four *days* eight hours. J. J. Cassini, however, in 1740, showed that the data collected by both observers were consistent with rotation in twenty-three hours twenty minutes.[836] So the matter rested until Schröter’s time. After watching nine years in vain, he at last, February 28, 1788, perceived the ordinarily uniform brightness of the planet’s disc to be marbled with a filmy streak, which returned periodically to the same position in about twenty-three hours twenty-eight minutes. This approximate estimate was corrected by the application of a more definite criterion. On December 28, 1789, the southern horn of the crescent Venus was seen truncated, an outlying lucid point interrupting the darkness beyond. Precisely the same appearance recurred two years later, giving for the planet's rotation a period of 23h. 21m.[837] To this only twenty-two seconds were added by De Vico, as the result of over 10,000 observations made with the Cauchoix refractor of the Collegio Romano, 1839-41.[838] The axis of rotation was found to be much more bowed towards the orbital plane than that of the earth, the equator making with it an angle of 53° 11′.

These conclusions inspired, it is true, much distrust, consequently there were no received ideas on the subject to be subverted. Nevertheless, a shock of surprise was felt at Schiaparelli's announcement, early in 1890,[839] that Venus most probably rotates after the fashion just previously ascribed to Mercury. A continuous series of observations, from November, 1877, to February, 1878, with their records in above a hundred drawings, supplied the chief part of the data upon which he rested his conclusions. They certainly appeared exceptionally well-grounded; and the doubts at first qualifying them were removed by a fresh set of determinations in July, 1895.[840] Most observers had depended, in their attempts to ascertain the rotation-period of Venus, upon evanescent shadings, most likely of atmospheric origin, and scarcely recognisable from day to day. Schiaparelli fixed his attention upon round, defined, lustrously white spots, the presence of which near the cusps of the illuminated crescent has been attested for close upon two centuries. His steady watch over them showed the invariability of their position with regard to the terminator; and this is as much as to say that the regions of day and night do not shift on the surface of the planet. In other words, she keeps the same face always turned towards the sun. Moreover, since her orbit is nearly circular, libratory effects are very small. They amount in fact to only just one-thirtieth of those serving to modify the severe contrasts of climate in Mercury.

Confirmatory evidence of Schiaparelli's result for Venus is not wanting. Thus, observations irreconcilable with a swift rate of rotation were made at Bothkamp in 1871 by Vogel and Lohse;[841] and a drawing executed by Professor Holden with the great Washington reflector, December 15, 1877, showed the same markings in the positions recorded at Milan to have been occupied by them eight hours previously. Further, a series of observations, carried out by M. Perrotin at Nice, May 15 to October 4, 1890, and from Mount Mounier in 1895-6, with the special aim of testing the inference of synchronous rotation and revolution, proved strongly corroborative of it.[842] A remarkable collection of drawings made by Mr. Lowell in 1896 appeared decisive in its favour;[843] Tacchini at Rome,[844] Mascari at Catania and Etna,[845] Cerulli at Terano,[846] obtained in 1892-6 evidence similar in purport. On the other hand, Niesten of Brussels found reason to revert to Vico's discarded elements for the planet's rotation;[847] and Trouvelot,[848] Stanley Williams,[849] Villiger,[850] and Leo Brenner,[851] so far agreed with him as to adopt a period of approximately twenty-four hours. Finally, E. Von Oppolzer suggested an appeal to the spectroscope;[852] and Bélopolsky secured in 1900[853] spectrograms apparently marked by the minute displacements corresponding to a rapid rate of axial movement. But they were avowedly taken only as an experiment, with unsuitable apparatus; and the desirable verification of their supposed import is not yet forthcoming. Until it is, Schiaparelli's period of 225 days must be allowed to hold the field.

Effects attributed to great differences of level in the surface of Venus have struck many observers. Francesco Fontana at Naples in 1643 noticed irregularities along the inner edge of the crescent.[854] Lahire in 1700 considered them—regard being had to difference of distance—to be much more strongly marked than those visible in the moon.[855] Schröter's assertions to the same effect, though scouted with some unnecessary vehemence by Herschel,[856] have since been repeatedly confirmed; amongst others by Mädler, De Vico, Langdon, who in 1873 saw the broken line of the terminator with peculiar distinctness through a veil of auroral cloud;[857] by Denning,[858] March 30, 1881, despite preliminary impressions to the contrary, as well as by C. V. Zenger at Prague, January 8, 1883. The great mountain mass, presumed to occasion the periodical blunting of the southern horn, was precariously estimated by the Lilienthal observer to rise to the prodigious height of nearly twenty-seven miles, or just five times the elevation of Mount Everest! Yet the phenomenon persists, whatever may be thought of the explanation. Moreover, the speck of light beyond, interpreted as the visible sign of a detached peak rising high enough above the encircling shadow to catch the first and last rays of the sun, was frequently discerned by Baron Van Ertborn in 1876;[859] while an object near the northern horn of the crescent, strongly resembling a lunar ring-mountain, was delineated both by De Vico in 1841 and by Denning forty years later.

We are almost equally sure that Venus, as that the earth is encompassed with an atmosphere. Yet, notwithstanding luminous appearances plainly due to refraction during the transits both of 1761 and 1769, Schröter, in 1792, took the initiative in coming to a definite conclusion on the subject.[860] It was founded, first, on the rapid diminution of brilliancy towards the terminator, attributed to atmospheric absorption; next, on the extension beyond a semicircle of the horns of the crescent; lastly, on the presence of a bluish gleam illuminating the early hours of the Cytherean night with what was taken to be genuine twilight. Even Herschel admitted that sunlight, by the same effect through which the heavenly bodies show *visibly above* our horizons while still *geometrically below* them, appeared to be bent round the shoulder of the globe of Venus. Ample confirmation of the fact has since been afforded. At Dorpat in May, 1849, the planet being within 3° 26′ of inferior conjunction, Mädler found the arms of waning light upon the disc to embrace no less than 240° of its extent;[861] and in December, 1842, Mr. Guthrie, of Bervie, N.B., actually observed, under similar conditions, the whole circumference to be lit up with a faint nebulous glow.[862] The same curious phenomenon was intermittently seen by Mr. Leeson Prince at Uckfield in September, 1861;[863] but with more satisfactory distinctness by Mr. C. S. Lyman of Yale College,[864] before and after the conjunction of December 11, 1866, and during nearly five hours previous to the transit of 1874, when the yellowish ring of refracted light showed at one point an approach to interruption, possibly through the intervention of a bank of clouds. Again, on December 2, 1898, Venus being 1° 45′ from the sun's centre, Mr. H. N. Russell, of the Halsted Observatory, descried the coalescence of the cusps, and founded on the observation a valuable discussion of such effects.[865] Taking account of certain features in the case left unnoticed by Neison[866] and Proctor,[867] he inferred from them the presence of a Cytherean atmosphere considerably less refractive than our own, although possibly, in its lower strata, encumbered with dust or haze.

Similar appearances are conspicuous during transits. But while the Mercurian halo is characteristically seen on the sun, the "silver thread" round the limb of Venus commonly shows on the part *off* the sun. There are, however, instances of each description in both cases. Mr. Grant, in collecting the records of physical phenomena accompanying the transits of 1761 and 1769, remarks that no one person saw both kinds of annulus, and argues a dissimilarity in their respective modes of production.[868] Such a dissimilarity probably exists, in the sense that the inner section of the ring is illusory, the outer, a genuine result of the bending of light in a gaseous envelope; but the distinction of separate visibility has not been borne out by recent experience. Several of the Australian observers during the transit of 1874 witnessed the complete phenomenon. Mr. J. Macdonnell, at Eden, saw a "shadowy nebulous ring" surround the whole disc when ingress was two-thirds accomplished; Mr. Tornaghi, at Goulburn, perceived a halo, entire and unmistakable, at half egress.[869] Similar observations were made at Sydney,[870] and were renewed in 1882 by Lescarbault at Orgères, by Metzger in Java, and by Barnard at Vanderbilt University.[871]

Spectroscopic indications of aqueous vapour as present in the atmosphere of Venus, were obtained in 1874 and 1882, by Tacchini and Riccò in Italy, and by Young in New Jersey.[872] Janssen, however, who made a special study of the point subsequently to the transit of 1882, found them much less certain than he had anticipated;[873] and Vogel, by repeated examinations, 1871-73, could detect only the very slightest variations from the pattern of the solar spectrum. Some additions there indeed seem to be in the thickening of a few water and oxygen-lines; but so nearly evanescent as to induce the persuasion that most of the light we receive from Venus has traversed only the tenuous upper portion of its atmosphere.[874] It is reflected, at any rate, with comparatively slight diminution. On the 26th and 27th of September, 1878, a close conjunction gave Mr. James Nasmyth the rare opportunity of watching Venus and Mercury for several hours side by side in the field of his reflector; when the former appeared to him like clean silver, the latter as dull as lead or zinc.[875] Yet the light *incident* upon Mercury is, on an average, three and a half times as strong as the light reaching Venus. Thus, the reflective power of Venus must be singularly strong. And we find, accordingly, from a combination of Zöllner's with Müller's results, that its albedo is but little inferior to that of new-fallen snow; in other words, it gives back 77 per cent. of the luminous rays impinging upon it.

This extraordinary brilliancy would be intelligible were it permissible to suppose that we see nothing of the planet but a dense canopy of clouds. But the hypothesis is discountenanced by the Flagstaff observations, and is irreconcilable with the visibility of mountainous elevations, and permanent surface-markings. To Mr. Lowell these were so distinct and unchanging as to furnish data for a chart of the Cytherean globe, and the peculiar arrangement of divergent shading exhibited in it cannot off-hand be set down as unreal, in view of Perrotin's earlier discernment of analogous linear traces. Gruithuisen's "snow-caps,"[876] however—it is safe to say—do not exist as such; although shining regions near the poles form a well-attested trait of the strange Cytherean landscape.

The "secondary," or "ashen light," of Venus was first noticed by Riccioli in 1643; it was seen by Derham about 1715, by Kirch in 1721, by Schröter and Harding in 1806;[877] and the reality of the appearance has since been authenticated by numerous and trustworthy observations. It is precisely similar to that of the "old moon in the new moon's arms"; and Zenger, who witnessed it with unusual distinctness, January 8, 1883,[878] supposes it due to the same cause—namely, to the faint gleam of reflected earth-light from the night-side of the planet. When we remember, however, that "full earth-light" on Venus, at its nearest, has little more than 1/12000 its intensity on the moon, we see at once that the explanation is inadequate. Nor can Professor Safarik's,[879] by phosphorescence of the warm and teeming oceans with which Zöllner[880] regarded the globe of Venus as mainly covered, be seriously entertained. Vogel's suggestion is more plausible. He and O. Lohse, at Bothkamp, November 3 to 11, 1871, saw the dark hemisphere *partially* illuminated by secondary light, extending 30° from the terminator, and thought the effect might be produced by a very extensive twilight.[881] Others have had recourse to the analogy of our auroræ, and J. Lamp suggested that the grayish gleam, visible to him at Bothkamp, October 21 and 26, 1887,[882] might be an accompaniment of electrical processes connected with the planet's meteorology. Whatever the origin of the phenomenon, it may serve, on a night-enwrapt hemisphere, to dissipate some of the thick darkness otherwise encroached upon only by "the pale light of stars."

Venus was once supposed to possess a satellite. But belief in its existence has died out. No one, indeed, has caught even a deceptive glimpse of such an object during the last 125 years. Yet it was repeatedly and, one might have thought, well observed in the seventeenth and eighteenth centuries. Fontana "discovered" it in 1645; Cassini—an adept in the art of seeing—recognised it in 1672, and again in 1686; Short watched it for a full hour in 1740 with varied instrumental means; Tobias Mayer in 1759, Montaigne in 1761; several astronomers at Copenhagen in March, 1764, noted what they considered its unmistakable presence; as did Horrebow in 1768. But M. Paul Stroobant,[883] who in 1887 submitted all the available data on the subject to a searching examination, identified Horrebow's satellite with θ Libræ, a fifth-magnitude star; and a few other apparitions were, by his industry, similarly explained away. Nevertheless, several withstood all efforts to account for them, and together form a most curious case of illusion. For it is quite certain that Venus has no such conspicuous attendant.

The third planet encountered in travelling outward from the sun is the abode of man. He has in consequence opportunities for studying its physical habitudes altogether different from the baffling glimpse afforded to him of the other members of the solar family.

Regarding the earth, then, a mass of knowledge so varied and comprehensive has been accumulated as to form a science—or rather several sciences—apart. But underneath all lie astronomical relations, the recognition and investigation of which constitute one of the most significant intellectual events of the present century.

It is indeed far from easy to draw a line of logical distinction between items of knowledge which have their proper place here, and those which should be left to the historian of geology. There are some, however, of which the cosmical connections are so close that it is impossible to overlook them. Among these is the ascertainment of the solidity of the globe. At first sight it seems difficult to conceive what the apparent positions of the stars can have to do with subterranean conditions; yet it was from star measurements alone that Hopkins, in 1839, concluded the earth to be solid to a depth of at least 800 or 1,000 miles.[884] His argument was, that if it were a mere shell filled with liquid, precession and nutation would be much larger than they are observed to be. For the shell alone would follow the pull of the sun and moon on its equatorial girdle, leaving the liquid behind; and being thus so much the lighter, would move the more readily. There is, it is true, grave reason to doubt whether this reasoning corresponds with the actual facts of the case;[885] but the conclusion to which it led has been otherwise affirmed and extended.

Indications of an identical purport have been derived from another kind of external disturbance, affecting our globe through the same agencies. Lord Kelvin (then Sir William Thomson) pointed out in 1862[886] that tidal influences are brought to bear on land as well as on water, although obedience to them is perceptible only in the mobile element. Some bodily distortion of the earth's figure *must*, however, take place, unless we suppose it of absolute or "preternatural" rigidity, and the amount of such distortion can be determined from its effect in diminishing oceanic tides below their calculated value. For if the earth were perfectly plastic to the stresses of solar and lunar gravity, tides—in the ordinary sense—would not exist. Continents and oceans would swell and subside together. It is to the *difference* in the behaviour of solid and liquid terrestrial constituents that the ebb and flow of the waters are due.

Six years later, the distinguished Glasgow professor suggested that this criterion might, by the aid of a prolonged series of exact tidal observations, be practically applied to test the interior condition of our planet.[887] In 1882, accordingly, suitable data extending over thirty-three years having at length become available, Mr. G. H. Darwin performed the laborious task of their analysis, with the general result that the "effective rigidity" of the earth's mass must be *at least* as great as that of steel.[888]

Ratification from an unexpected quarter has lately been brought to this conclusion. The question of a possible mobility in the earth's axis of rotation has often been mooted. Now at last it has received an affirmative reply. Dr. Küstner detected, in his observations of 1884-85, effects apparently springing from a minute variation in the latitude of Berlin. The matter having been brought before the International Geodetic Association in 1888, special observations were set on foot at Berlin, Potsdam, Prague, and Strasbourg, the upshot of which was to bring plainly to view synchronous, and seemingly periodic fluctuations of latitude to the extent of half a second of arc. The reality of these was verified by an expedition to Honolulu in 1891-92, the variations there corresponding inversely to those simultaneously determined in Europe.[889] Their character was completely defined by Mr. S. C. Chandler's discussion in October, 1891.[890] He showed that they could be explained by supposing the pole of the earth to describe a circle with a radius of thirty feet in a period of fourteen months. Confirmation of this hypothesis was found by Dr. B. A. Gould in the Cordoba observations,[891] and it was provided with a physical basis through the able co-operation of Professor Newcomb.[892] The earth, owing to its ellipsoidal shape, should, apart from disturbance, rotate upon its "axis of figure," or shortest diameter; since thus alone can the centrifugal forces generated by its spinning balance each other. Temporary causes, however, such as heavy falls of snow or rain limited to one continental area, the shifting of ice-masses, even the movements of winds, may render the globe slightly lop-sided, and thus oblige it to forsake its normal axis, and rotate on one somewhat divergent from it. This "instantaneous axis" (for it is incessantly changing) must, by mathematical theory, revolve round the axis of figure in a period of 306 days. Provided, that is to say, the earth were a perfectly rigid body. But it is far from being so; it yields sensibly to every strain put upon it; and this yielding tends to protract the time of circulation of the displaced pole. The length of its period, then, serves as a kind of measure of the plasticity of the globe; which, according to Newcomb's and S. S. Hough's independent calculations,[893] seems to be a little less than that of steel. In an earth compacted of steel, the instantaneous axis would revolve in 441 days; in the actual earth, the process is accomplished in 428 days. By this new path, accordingly, astronomers have been led to an identical estimate of the consistence of our globe with that derived from tidal investigations.

Variations of latitude are intrinsically complex. To produce them, an incalculable interplay of causes must be at work, each with its proper period and law of action.[894] All the elements of the phenomenon are then in a perpetual state of flux,[895] and absorb for their continual redetermination, the arduous and combined labours of many astronomers. Nor is this trouble superfluous. Minute in extent though they be, the shiftings of the pole menace the very foundations of exact celestial science; their neglect would leave the entire fabric insecure. Just at the beginning of the present century they reached a predicted minimum, but are expected again to augment their range after the year 1902. The interesting suggestion has been made by Mr. J. Halm that such fluctuations are, in some obscure way, affected by changes in solar activity, and conform like them to an eleven-year cycle.[896]

In a paper read before the Geological Society, December 15, 1830,[897] Sir John Herschel threw out the idea that the perplexing changes of climate revealed by the geological record might be explained through certain slow fluctuations in the eccentricity of the earth's orbit, produced by the disturbing action of the other planets. Shortly afterwards, however, he abandoned the position as untenable;[898] and it was left to the late Dr. James Croll, in 1864[899] and subsequent years, to reoccupy and fortify it. Within restricted limits (as Lagrange and, more certainly and definitely, Leverrier proved), the path pursued by our planet round the sun alternately contracts, in the course of ages, into a moderate ellipse, and expands almost to a circle, the major axis, and consequently the mean distance, remaining invariable. Even at present, when the eccentricity approaches a minimum, the sun is nearer to us in January than in July by above three million miles, and some 850,000 years ago this difference was more than four times as great. Dr. Croll brought together[900] a mass of evidence to support the view, that, at epochs of considerable eccentricity, the hemisphere of which the winter, occurring at aphelion, was both intensified and prolonged, must have undergone extensive glaciation; while the opposite hemisphere, with a short, mild winter, and long, cool summer, enjoyed an approach to perennial spring. These conditions were exactly reversed at the end of 10,500 years, through the shifting of the perihelion combined with the precession of the equinoxes, the frozen hemisphere blooming into a luxuriant garden as its seasons came round to occur at the opposite sites of the terrestrial orbit, and the vernal hemisphere subsiding simultaneously into ice-bound rigour.[901] Thus a plausible explanation was offered of the anomalous alternations of glacial and semi-tropical periods, attested, on incontrovertible geological evidence, as having succeeded each other in times past over what are now temperate regions. They succeeded each other, it is true, with much less frequency and regularity than the theory demanded; but the discrepancy was overlooked or smoothed away. The most recent glacial epoch was placed by Dr. Croll about 200,000 years ago, when the eccentricity of the earth's orbit was 3·4 times as great as it is now. At present a faint representation of such a state of things is afforded by the southern hemisphere. One condition of glaciation in the coincidence of winter with the maximum of remoteness from the sun, is present; the other—a high eccentricity—is deficient. Yet the ring of ice-bound territory hemming in the southern pole is well known to be far more extensive than the corresponding region in the north.

The verification of this ingenious hypothesis depends upon a variety of intricate meteorological conditions, some of which have been adversely interpreted by competent authorities.[902] What is still more serious, its acceptance seems precluded by time-relations of a simple kind. Dr. Wright[903] has established with some approach to certainty that glacial conditions ceased in Canada and the United States about ten or twelve thousand years ago. The erosive action of the Falls of Niagara qualifies them to serve as a clepsydra, or water-clock on a grand scale; and their chronological indications have been amply corroborated elsewhere and otherwise on the same continent. The astronomical Ice Age, however, should have been enormously more antique. No reconciliation of the facts with the theory appears possible.

The first attempt at an experimental estimate of the "mean density" of the earth was Maskelyne's observation in 1774 of the deflection of a plumb-line through the attraction of Schehallien. The conclusion thence derived, that our globe weighs 4-1/2 times as much as an equal bulk of water,[904] was not very exact. It was considerably improved upon by Cavendish, who, in 1798, brought into use the "torsion-balance" constructed for the same purpose by John Michell. The resulting estimate of 5·48 was raised to 5·66 by Francis Baily's elaborate repetition of the process in 1838-42. From experiments on the subject made in 1872-73 by Cornu and Baille the slightly inferior value of 5·56 was derived; and it was further shown that the data collected by Baily, when corrected for a systematic error, gave practically the same result (5·55).[905] M. Wilsing's of 5·58, obtained at Potsdam in 1889,[906] nearly agreed with it; while Professor Poynting, by means of a common balance, arrived at a terrestrial mean density of 5·49.[907] Professor Boys next entered the field with an exquisite apparatus, in which a quartz fibre performed the functions of a torsion-rod; and the figure 5·53 determined by him, and exactly confirmed by Dr. Braun's research at Mariaschein, Bohemia, in 1896,[908] may be called the standard value of the required datum. Newton's guess at the average weight of the earth as five or six times that of water has thus been curiously verified.

Operations for determining the figure of the earth were carried out during the last century on an unprecedented scale. The Russo-Scandinavian arc, of which the measurement was completed under the direction of the elder Struve in 1855, reached from Hammerfest to Ismailia on the Danube, a length of 25° 20′. But little inferior to it was the Indian arc, begun by Lambton in the first years of the century, continued by Everest, revised and extended by Walker. Both were surpassed in compass by the Anglo-French arc, which embraced 28°; and considerable segments of meridians near the Atlantic and Pacific shores of North America were measured under the auspices of the United States Coast Survey. But these operations shrink into insignificance by comparison with Sir David Gill's grandiose scheme for uniting two hemispheres by a continuous network of triangulation. The history of geodesy in South Africa began with Lacaille's measurements in 1752. They were repeated and enlarged in scope by Sir Thomas Maclear in 1841-48;

and his determinations prepared the way for a complete survey of Cape Colony and Natal, executed during the ten years 1883-92 by Colonel Morris, R.E., under the direction of Sir David Gill.[909] Bechuanaland and Rhodesia were subsequently included in the work; and the Royal Astronomer obtained, in 1900, the support of the International Geodetic Association for its extension to the mouth of the Nile. Nor was this the limit of his design. By carrying the survey along the Levantine coast, connection can be established with Struve's system, and the magnificent amplitude of 105° will be given to the conjoined African and European arcs. Meantime, the French have undertaken the remeasurement of Bouguer's Peruvian arc, and a corresponding Russo-Swedish[910] enterprise is progressing in Spitzbergen; so that abundant materials will ere long be provided for fresh investigations of the shape and size of our planet. The smallness of the outstanding uncertainty can be judged of by comparing J. B. Listing's[911] with General Clarke's[912] results, published in the same year (1878). Listing stated the dimensions of the terrestrial spheroid as follows: Equatorial radius = 3,960 miles; polar radius = 3,947 miles; ellipticity = 1/288·5. Clarke's corresponding figures were: 3,963 and 3,950 miles, giving an ellipticity of 1/293·5. The value of the latter fraction at present generally adopted is 1/292; that is to say, the thickness of the protuberant equatorial ring is held to be 1/292 of the equatorial radius. From astronomical considerations, it is true, Newcomb estimated the ratio at 1/308;[913] but for obtaining this particular datum, geodetical methods are unquestionably to be preferred.

The moon possesses for us a unique interest. She in all probability shared the origin of the earth; she perhaps prefigures its decay. She is at present its minister and companion. Her existence, so far as we can see, serves no other purpose than to illuminate the darkness of terrestrial nights, and to measure, by swiftly-recurring and conspicuous changes of aspect, the long span of terrestrial time. Inquiries stimulated by visible dependence, and aided by relatively close vicinity, have resulted in a wonderfully minute acquaintance with the features of the single lunar hemisphere open to our inspection.

Selenography, in the modern sense, is little more than a hundred years old. It originated with the publication in 1791 of Schröter's *Selenotopographische Fragmente*.[914] Not but that the lunar surface had already been diligently studied, chiefly by Hevelius, Cassini, Riccioli, and Tobias Mayer; the idea, however, of investigating the moon's physical condition, and detecting symptoms of the activity there of natural forces through minute topographical inquiry, first obtained effect at Lilienthal. Schröter's delineations, accordingly, imperfect though they were, afforded a starting-point for a *comparative* study of the superficial features of our satellite.

The first of the curious objects which he named "rills" was noted by him in 1787. Before 1801 he had found eleven; Lohrmann added 75; Mädler 55; Schmidt published in 1866 a catalogue of 425, of which 278 had been detected by himself;[915] and he eventually brought the number up to nearly 1,000. They are, then, a very persistent lunar feature, though wholly without terrestrial analogue. There is no difference of opinion as to their nature. They are quite obviously clefts in a rocky surface, 100 to 500 yards deep, usually a couple of miles across, and pursuing straight, curved, or branching tracks up to 150 miles in length. As regards their origin, the most probable view is that they are fissures produced in cooling; but Neison inclines to consider them rather as dried watercourses.[916]

On February 24, 1792, Schröter perceived what he took to be distinct traces of a lunar twilight, and continued to observe them during nine consecutive years.[917] They indicated, he thought, the presence of a shallow atmosphere, about 29 times more tenuous than our own. Bessel, on the other hand, considered that the only way of "saving" a lunar atmosphere was to deny it any refractive power, the sharpness and suddenness of star-occultations negativing the possibility of gaseous surroundings of greater density (admitting an extreme supposition) than 1/500 that of terrestrial air.[918] Newcomb places the maximum at 1/400. Sir John Herschel concluded "the non-existence of any atmosphere at the moon's edge having 1/1980 part of the density of the earth's atmosphere."[919]

This decision was fully borne out by Sir William Huggins's spectroscopic observation of the disappearance behind the moon's limb of the small star ε Piscium, January 4, 1865.[920] Not the slightest sign of selective absorption or unequal refraction was discernible. The entire spectrum went out at once, as if a slide had suddenly dropped over it. The spectroscope has uniformly told the same tale; for M. Thollon's observation during the total solar eclipse at Sohag of a supposed thickening at the moon's rim, of certain dark lines in the solar spectrum, is now acknowledged to have been illusory. Moonlight, analysed with the prism, is found to be pure reflected sunlight, diminished in *quantity*, owing to the low reflective capability of the lunar surface, to less than one-fifth its incident intensity, but wholly unmodified in *quality*.

Nevertheless, the diameter of the moon appeared from the Greenwich observations discussed by Airy in 1865[921] to be 4′ smaller than when directly measured; and the effect would be explicable by refraction in a lunar atmosphere 2,000 times thinner than our own at the sea-level. But the difference was probably illusory. It resulted in part, if not wholly, from the visual enlargement by irradiation of the bright disc of the moon. Professor Comstock, employing the 16-inch Clark equatoreal of the Washburn Observatory, found in 1897 the refractive displacements of occulted stars so trifling as to preclude the existence of a permanent lunar atmosphere of much more than 1/5000 the density of the terrestrial envelope.[922] The possibility, however, was admitted that, on the illuminated side of the moon, temporary exhalations of aqueous vapour might arise from ice-strata evaporated by sun-heat. Meantime, some renewed evidence of actual crepuscular gleams on the moon had been gathered by MM. Paul and Prosper Henry of the Paris Observatory, as well as by Mr. W. H. Pickering, in the pure air of Arequipa, at an altitude of 8,000 feet above the sea.

[923] An occultation of Jupiter, too, observed by him August 12, 1892,[924] was attended with a slight flattening of the planet's disc through the effect, it was supposed, of lunar refraction—but of refraction in an atmosphere possessing, at the most, 1/4000 the density at the sea-level of terrestrial air, and capable of holding in equilibrium no more than 1/250 of an inch of mercury. Yet this small barometric value corresponds, Mr. Pickering remarks, "to a pressure of hundreds of tons per square mile of the lunar surface." The compression downward of gaseous strata on the moon should, in any case, proceed very gradually, owing to the slight power of lunar gravity,[925] and they might hence play an important part in the economy of our satellite while evading spectroscopic and other tests. Thus—as Mr. Ranyard remarked[926]—the cliffs and pinnacles of the moon bear witness, by their unworn condition, to the efficiency of atmospheric protection against meteoric bombardment; and Mr. Pickering shows that it could be afforded by such a tenuous envelope as that postulated by him.

The first to emulate Schröter's selenographical zeal was Wilhelm Gotthelf Lohrmann, a land-surveyor of Dresden, who, in 1824, published four out of twenty-five sections of the first scientifically executed lunar chart, on a scale of 37-1/2 inches to a lunar diameter. His sight, however, began to fail three years later, and he died in 1840, leaving materials from which the work was completed and published in 1878 by Dr. Julius Schmidt, late director of the Athens Observatory. Much had been done in the interim. Beer and Mädler began at Berlin in 1830 their great trigonometrical survey of the lunar surface, as yet neither revised nor superseded. A map, issued in four parts, 1834-36, on nearly the same scale as Lohrmann's, but more detailed and authoritative, embodied the results. It was succeeded, in 1837, by a descriptive volume bearing the imposing title, *Der Mond; oder allgemeine vergleichende Selenographie*. This summation of knowledge in that branch, though in truth leaving many questions open, had an air of finality which tended to discourage further inquiry.[927] It gave form to a reaction against the sanguine views entertained by Hevelius, Schröter, Herschel and Gruithuisen as to the possibilities of agreeable residence on the moon, and relegated the "Selenites," one of whose cities Schröter thought he had discovered, and of whose festal processions Gruithuisen had not despaired of becoming a spectator, to the shadowy land of the Ivory Gate. All examples of change in lunar formations were, moreover, dismissed as illusory. The light contained in the work was, in short, a "dry light," not stimulating to the imagination. "A mixture of a lie," Bacon shrewdly remarks, "doth ever add pleasure." For many years, accordingly, Schmidt had the field of selenography almost to himself.

Reviving interest in the subject was at once excited and displayed by the appointment, in 1864, of a Lunar Committee of the British Association. The indirect were of greater value than the direct fruits of its labours. An English school of selenography rose into importance. Popularity was gained for the subject by the diffusion of works conspicuous for ingenuity and research. Nasmyth's and Carpenter's beautifully illustrated volume (1874) was succeeded, after two years, by a still more weighty contribution to lunar science in Mr. Neison's well-known book, accompanied by a map, based on the survey of Beer and Mädler, but adding some 500 measures of positions, besides the representation of several thousand new objects. With Schmidt's *Charte der Gebirge der Mondes*, Germany once more took the lead. This splendid delineation, built upon Lohrmann's foundation, embraced the detail contained in upwards of 3,000 original drawings, representing the labour of thirty-four years. No less than 32,856 craters are represented in it, on a scale of seventy-five inches to a diameter. An additional help to lunar inquiries was provided at the same time in this country by the establishment, through the initiative of the late Mr. W. R. Birt, of the Selenographical Society.

But the strongest incentive to diligence in studying the rugged features of our celestial helpmate has been the idea of probable or actual variation in them. A change always seems to the inquisitive intellect of man like a breach in the defences of Nature's secrets, through which it may hope to make its way to the citadel. What is desirable easily becomes credible; and thus statements and rumours of lunar convulsions have successively, during the last hundred years, obtained credence, and successively, on closer investigation, been rejected. The subject is one as to which illusion is peculiarly easy. Our view of the moon's surface is a bird's-eye view. Its conformation reveals itself indirectly through irregularities in the distribution of light and darkness. The forms of its elevations and depressions can be inferred only from the shapes of the black, unmitigated shadows cast by them. But these shapes are in a state of perpetual and bewildering fluctuation, partly through changes in the angle of illumination, partly through changes in our point of view, caused by what are called the moon's "librations."[928] The result is, that no single observation can be *exactly* repeated by the same observer, since identical conditions recur only after the lapse of a great number of years.

Local peculiarities of surface, besides, are liable to produce perplexing effects. The reflection of earth-light at a particular angle from certain bright summits completely, though temporarily, deceived Herschel into the belief that he had witnessed, in 1783 and 1787, volcanic outbursts on the dark side of the moon. The persistent recurrence, indeed, of similar appearances under circumstances less amenable to explanation inclined Webb to the view that effusions of native light actually occur.[929] More cogent proofs must, however, be adduced before a fact so intrinsically improbable can be admitted as true.

But from the publication of Beer and Mädler's work until 1866, the received opinion was that no genuine sign of activity had ever been seen, or was likely to be seen, on our satellite; that her face was a stereotyped page, a fixed and irrevisable record of the past. A profound sensation, accordingly, was produced by Schmidt's announcement, in October, 1866, that the crater "Linné," in the Mare Serenitatis, had disappeared,[930] effaced, as it was supposed, by an igneous outflow. The case seemed undeniable, and is still dubious. Linné had been known to Lohrmann and Mädler, 1822-32, as a deep crater, five or six miles in diameter, the third largest in the dusky plain known as the "Mare Serenitatis"; and

Schmidt had observed and drawn it, 1840-43, under a practically identical aspect. Now it appears under high light as a whitish spot, in the centre of which, as the rays begin to fall obliquely, a pit, scarcely two miles across, emerges into view.[931] The crateral character of this comparatively minute depression was detected by Father Secchi, February 11, 1867.

This is not all. Schröter's description of Linné, as seen by him November 5, 1788, tallies quite closely with modern observation;[932] while its inconspicuousness in 1797 is shown by its omission from Russell's lunar globe and maps.[933] We are thus driven to adopt one of two suppositions: either Lohrmann, Mädler, and Schmidt were entirely mistaken in the size and importance of Linné, or a real change in its outward semblance supervened during the first half of the century, and has since passed away, perhaps again to recur. The latter hypothesis seems the more probable: and its probability is strengthened by much evidence of actual obscuration or variation of tint in other parts of the lunar surface, more especially on the floor of the great "walled plain" named "Plato."[934] From a re-examination with a 13-inch refractor at Arequipa in 1891-92, of this region, and of the Mare Serenitatis, Mr. W. H. Pickering inclines to the belief that lunar volcanic action, once apparently so potent, is not yet wholly extinct.[935]

An instance of an opposite kind of change was alleged by Dr. Hermann J. Klein of Cologne in March, 1878.[936] In Linné the obliteration of an old crater had been assumed; in "Hyginus N.," the formation of a new crater was asserted. Yet, quite possibly, the same cause may have produced the effects thought to be apparent in both. It is, however, far from certain that any real change has affected the neighbourhood of Hyginus. The novelty of Klein's observation of May 19, 1877, may have consisted simply in the detection of a hitherto unrecognised feature. The region is one of complex formation, consequently of more than ordinary liability to deceptive variations in aspect under rapid and entangled fluctuations of light and shade.[937] Moreover, it seems to be certain, from Messrs. Pratt and Capron's attentive study, that "Hyginus N." is no true crater, but a shallow, saucer-like depression, difficult of clear discernment.[938] Under suitable illumination, nevertheless, it contains, and is marked by, an ample shadow.[939]

In both these controverted instances of change, lunar photography was invoked as a witness; but, notwithstanding the great advances made in the art by De la Rue in this country, by Draper, and, above all, by Rutherford in America, without decisive results. Investigations of the kind began to assume a new aspect in 1890, when Professor Holden organised them at the Lick Observatory.[940] Autographic moon-pictures were no longer taken casually, but on system; and Dr. Weinek's elaborate study, and skilful reproductions of them at Prague,[941] gave them universal value. They were designed to provide materials for an atlas on the scale of Beer and Mädler's, of which some beautiful specimen-plates have been issued. At Paris, in 1894, with the aid of a large "equatoreal coudé," a work of similar character was set on foot by MM. Loewy and Puiseux. Its progress has been marked by the successive publication of five instalments of a splendid atlas, on a scale of about eight feet to the lunar diameter, accompanied by theoretical dissertations, designed to establish a science of "selenology." The moon's formations are thus not only delineated under every variety of light-incidence, but their meaning is sought to be elicited, and their history and mutual relations interpreted.[942] Henceforth, at any rate, the lunar volcanoes can scarcely, without notice taken, breathe hard in their age-long sleep.

Melloni was the first to get undeniable heating effects from moonlight. His experiments, made on Mount Vesuvius early in 1846,[943] were repeated with like result by Zantedeschi at Venice four years later. A rough measure of the intensity of those effects was arrived at by Piazzi Smyth at Guajara, on the Peak of Teneriffe, in 1856. At a distance of fifteen feet from the thermomultiplier, a Price's candle was found to radiate just twice as much heat as the full moon.[944] Then, after thirteen years, in 1869-72, an exact and extensive series of observations on the subject were made by the present Earl of Rosse. The lunar radiations, from the first to the last quarter, displayed, when concentrated with the Parsonstown three-foot mirror, appreciable thermal energy, increasing with the phase, and largely due to "dark heat," distinguished from the quicker-vibrating sort by inability to traverse a plate of glass. This was supposed to indicate an actual heating of the surface, during the long lunar day of 300 hours, to about 500° F.[945] (corrected later to 197°),[946] the moon thus acting as a direct radiator no less than as a reflector of heat. But the conclusion was very imperfectly borne out by Dr. Boeddicker's observations with the same instrument and apparatus during the total lunar eclipse of October 4, 1884.[947] This initial opportunity of measuring the heat phases of an eclipsed moon was used with the remarkable result of showing that the heat disappeared almost completely, though not quite simultaneously, with the light. Confirmatory evidence of the extraordinary promptitude with which our satellite parts with heat already to some extent appropriated, was afforded by Professor Langley's bolometric observations at Allegheny of the partial eclipse of September 23, 1885.[948] Yet it is certain that the moon sends us a perceptible quantity of heat *on its own account*, besides simply throwing back solar radiations. For in February, 1885, Professor Langley succeeded, after many fruitless attempts, in getting measures of a "lunar heat-spectrum." The incredible delicacy of the operation may be judged of from the statement that the sum-total of the thermal energy dispersed by his rock-salt prisms was insufficient to raise a thermometer fully exposed to it one-thousandth of a degree Centigrade! The singular fact was, however, elicited that this almost evanescent spectrum is made up of two superposed spectra, one due to reflection, the other, with a maximum far down in the infra-red, to radiation.[949] The corresponding temperature of the moon's sunlit surface Professor Langley considers to be about that of freezing water.[950] Repeated experiments having failed to get any thermal effects from the dark part of the moon, it was inferred that our satellite "has no internal heat sensible at the surface"; so that the radiations from the lunar soil giving the low maximum in the heat-spectrum, "must be due purely to solar heat which has been absorbed and almost immediately re-radiated." Professor Langley's explorations of the terra incognita of immensely long wave-lengths where lie the unseen heat-emissions from the earth into space, led him to the discovery that these, contrary to the received opinion, are in good part transmissible by our atmosphere, although they are completely intercepted by glass. Another important result of the Allegheny work was the abolition of the anomalous notion of the "temperature of space," fixed by Pouillet at -140° C. For space in itself can have no temperature, and stellar radiation is a negligible quantity. Thus, it is safe to assume "that a perfect thermometer suspended in space at the distance of the earth or moon from the sun, but shielded from its rays, would sensibly indicate the absolute zero,"[951] ordinarily placed at -273° C.

A "Prize Essay on the Distribution of the Moon's Heat" (The Hague), 1891, by Mr. Frank W. Very, who had taken an active part in Professor Langley's long-sustained inquiry, embodies the fruits of its continuation. They show the lunar disc to be tolerably uniform in thermal power. The brighter parts are also indeed hotter, but not much. The traces perceived of a slight retention of heat by the substances forming the lunar surface, agreed well with the Parsonstown observations of the total eclipse of the moon, January 28, 1888.[952] For they brought out an unmistakable divergence between the heat and light phases. A curious decrease of heat previous to the first touch of the earth's shadow upon the lunar globe remains unexplained, unless it be admissible to suppose the terrestrial atmosphere capable of absorbing heat at an elevation of 190 miles. The probable range of temperature on the moon was discussed by Professor Very in 1898.[953] He concluded it to be very wide. Hotter than boiling water under the sun's vertical rays, the arid surface of our dependent globe must, he found, cool in the 14-day lunar night to about the temperature of liquid air.

Although that fundamental part of astronomy known as "celestial mechanics" lies outside the scope of this work, and we therefore pass over in silence the immense labours of Plana, Damoiseau, Hansen, Delaunay, G. W. Hill, and Airy in reconciling the observed and calculated motions of the moon, there is one slight but significant discrepancy which is of such importance to the physical history of the solar system, that some brief mention must be made of it.

Halley discovered in 1693, by examining the records of ancient eclipses, that the moon was going faster then than 2,000 years previously—so much faster, as to have got ahead of the place in the sky she would otherwise have occupied, by about two of her own diameters. It was one of Laplace's highest triumphs to have found an explanation of this puzzling fact. He showed, in 1787, that it was due to a very slow change in the ovalness of the earth's orbit, tending, during the present age of the world, to render it more nearly circular. The pull of the sun upon the moon is thereby lessened; the counter-pull of the earth gets the upper hand; and our satellite, drawn nearer to us by something less than an inch each year,[954] proportionately quickens her pace. Many thousands of years hence the process will be reversed; the terrestrial orbit will close in at the sides, the lunar orbit will open out under the growing stress of solar gravity, and our celestial chronometer will lose instead of gaining time.

This is all quite true as Laplace put it; but it is not enough. Adams, the virtual discoverer of Neptune, found with surprise in 1853 that the received account of the matter was "essentially incomplete," and explained, when the requisite correction was introduced, only half the observed acceleration.[955] What was to be done with the remaining half? Here Delaunay, the eminent French mathematical astronomer, unhappily drowned at Cherbourg in 1872 by the capsizing of a pleasure-boat, came to the rescue.[956]

It is obvious to anyone who considers the subject a little attentively, that the tides must act to some extent as a friction-brake upon the rotating earth. In other words, they must bring about an almost infinitely slow lengthening of the day. For the two masses of water piled up by lunar influence on the hither and farther sides of our globe, strive, as it were, to detach themselves from the unity of the terrestrial spheroid, and to follow the movements of the moon. The moon, accordingly, holds them *against* the whirling earth, which revolves like a shaft in a fixed collar, slowly losing motion and gaining heat, eventually dissipated through space.[957] This must go on (so far as we can see) until the periods of the earth's rotation and of the moon's revolution coincide. Nay, the process will be continued—should our oceans survive so long—by the feebler tide-raising power of the sun, ceasing only when day and night cease to alternate, when one side of our planet is plunged in perpetual darkness and the other seared by unchanging light.

Here, then, we have the secret of the moon's turning always the same face towards the earth. It is that in primeval times, when the moon was liquid or plastic, an earth-raised tidal wave rapidly and forcibly reduced her rotation to its present exact agreement with her period of revolution. This was divined by Kant[958] nearly a century before the necessity for such a mode of action presented itself to any other thinker. In a weekly paper published at Königsberg in 1754, the modern doctrine of "tidal friction" was clearly outlined by him, both as regards its effects actually in progress on the rotation of the earth, and as regards its effects already consummated on the rotation of the moon—the whole forming a preliminary attempt at what he called a "natural history" of the heavens. His sagacious suggestion, however, remained entirely unnoticed until revived—it would seem independently—by Julius Robert Mayer in 1848;[959] while similar, and probably original, conclusions were reached by William Ferrel of Allensville, Kentucky, in 1858.[960]

Delaunay was not then the inventor or discoverer of tidal friction; he merely displayed it as an effective cause of change. He showed reason for believing that its action in checking the earth's rotation, far from being, as Ferrel had supposed, completely neutralised by the contraction of the globe through cooling, was a fact to be reckoned with in computing the movements, as well as in speculating on the history, of the heavenly bodies. The outstanding acceleration of the moon was thus at once explained. It was explained as apparent only—the reflection of a real lengthening, by one second in 100,000 years, of the day. But on this point the last word has not yet been spoken.

Professor Newcomb undertook in 1870 the onerous task of investigating the errors of Hansen's Lunar Tables as compared with observations prior to 1750. The results, published in 1878,[961] proved somewhat perplexing. They tend, in general, to reduce the amount of acceleration left unaccounted for by Laplace's gravitational theory, and proportionately to diminish the importance of the part played by tidal friction. But, in order to bring about this diminution, and at the same time conciliate Alexandrian and Arabian observations, it is necessary to reject *as total* the ancient solar eclipses known as those of Thales and Larissa. This may be a necessary, but it must be admitted to be a hazardous expedient. Its upshot was to indicate a possibility that the observed and calculated values of the moon's acceleration might after all prove to be identical; and the small outstanding discrepancy was still further diminished by Tisserand's investigation, differently conducted, of the same Arabian eclipses discussed by Newcomb.[962] The necessity of having recourse to a lengthening day is then less pressing than it seemed some time ago; and the effect, if perceptible in the moon's motion, should, M. Tisserand remarked, be proportionately so in the motions of all the other heavenly bodies. The presence of the apparent general acceleration that should ensue can be tested with most promise of success, according to the same authority, by delicate comparisons of past and future transits of Mercury.

Newcomb further showed that small residual irregularities are still found in the movements of our satellite, inexplicable either by any known gravitational influence, or by any *uniform* value that could be assigned to secular acceleration.[963] If set down to the account of imperfections in the "time-keeping" of the earth, it could only be on the arbitrary supposition of fluctuations in its rate of going themselves needing explanation. This, it is true, might be found in very slight changes of figure,[964] not altogether unlikely to occur. But into this cloudy and speculative region astronomers for the present decline to penetrate. They prefer, if possible, to deal only with calculable causes, and thus to preserve for their "most perfect of sciences" its special prerogative of assured prediction.

FOOTNOTES:

[796] *Neueste Beyträge zur Erweiterung der Sternkunde*, Bd. iii., p. 14 (1800).

[797] *Ibid.*, p. 24.

[798] *Phil. Trans.*, vol. xciii., p. 215.

[799] *Mem. Roy. Astr. Soc.*, vol. vi., p. 116.

[800] *Month. Not.*, vol. xix., pp. 11, 25.

[801] *Ibid.*, vol. xxxviii., p. 398.

[802] *Am. Jour. of Sc.*, vol. xvi., p. 124.

[803] *Wash. Obs.* for 1876, Part ii., p. 34.

[804] *Pop. Astr.*, vol. ii., p. 168; *Astr. Jour.*, No. 335.

[805] *Astr. and Astrophysics*, vol. xiii., p. 866.

[806] *Ibid.*, p. 867.

[807] *Month. Not.*, vol. xxiv., p. 18.

[808] *Ibid.*, vol. xxiii., p. 234 (Challis).

[809] *Untersuchungen über die Spectra der Planeten*, p. 9.

[810] *Sirius*, vol. vii., p. 131.

[811] *Potsdam Publ.*, No. 30; *Astr. Nach.*, No. 3,171; Frost, *Astr. and Astrophysics*, vol. xii., p. 619.

[812] Zöllner and Winnecke made it=O·13, *Astr. Nach.*, No. 2,245.

[813] *Neueste Beyträge*, Bd. iii., p. 50.

[814] *Astr. Jahrbuch*, 1804, pp. 97-102.

[815] Webb, *Celestial Objects*, p. 46 (4th ed.).

[816] *L'Astronomie*, t. ii., p. 141.

[817] *Observations sur les Planètes Vénus et Mercure*, p. 87.

[818] *Observatory*, vol. vi., p. 40.

[819] *Atti dell' Accad. dei Lincei*, t. v. ii., p. 283, 1889; *Astr. Nach.*, No. 2,944.

[820] *Astr. Nach.* No. 2,479.

[821] *Memoirs Amer. Acad.*, vol. xii., No. 4, p. 464.

[822] *Hist. de l'Astr.*, p. 682.

[823] *Comptes Rendus*, t. xlix., p. 379.

[824] *Comptes Rendus*, t. l., p. 40.

[825] *Ibid.*, p. 46.

[826] *Astr. Nach.*, Nos. 1,248 and 1,281.

[827] *Comptes Rendus*, t. lxxxiii., pp. 510, 561.

[828] *Handbuch der Mathematik*, Bd. ii., p. 327.

[829] *Comptes Rendus*, t. lxxxiii., p. 721.

[830] *Nature*, vol. xviii., pp. 461, 495, 539.

[831] Oppolzer, *Astr. Nach.*, No. 2,239.

[832] *Ibid.*, Nos. 2,253-4 (C. H. F. Peters).

[833] *Ibid.*, Nos. 2,263 and 2,277. See also Tisserand in *Ann. Bur. des Long.*, 1882, p. 729.

[834] See J. Bauschinger's *Untersuchungen* (1884), summarised in *Bull. Astr.*, t. i., p. 506, and *Astr. Nach.*, No. 2,594. Newcomb finds the anomalous motion of the perihelion to be even larger (43′ instead of 38′) than Leverrier made it. *Month. Not.*, February, 1884, p. 187. Harzer's attempt to account for it in *Astr. Nach.*, No. 3,030, is more ingenious than successful.

[835] *Jour. des Sçavans*, December, 1667, p. 122.

[836] *Élémens d'Astr.*, p. 525. Cf. Chandler, *Pop. Astr.*, February, 1897, p. 393.

[837] *Beobachtungen über die sehr beträchtlichen Gebirge und Rotation der Venus*, 1792, p. 35. Schröter's final result in 1811 was 23h. 21m. 7·977s. *Monat. Corr.*, Bd. xxv., p. 367.

[838] *Astr. Nach.*, No. 404.

[839] *Rendiconti del R. Istituto Lombardo*, t. xxiii., serie ii.

[840] *Astr. Nach.*, No. 3,304.

[841] *Bothkamp Beobachtungen*, Heft ii., p. 120.

[842] *Comptes Rendus*, t. cxi., p. 542; t. cxxii., p. 395.

[843] *Month. Not.*, vol. lvii., p. 402; *Astr. Nach.*, No. 3,406.

[844] *Mem. Spettroscopisti Italiani*, t. xxv., p. 93; *Nature*, vol. liii., p. 306.

[845] *Astr. Nach.*, No. 3,329.

[846] *Ibid.*

[847] *Bull. de l'Acad. de Belgique*, t. xxi., p. 452, 1891.

[848] *Observations sur les Planètes Vénus et Mercure*, 1892.

[849] *Astr. Nach.*, No. 3,300.

[850] *Ibid.*, No. 3,332.

[851] *Ibid.*, No. 3,314.

[852] *Ibid.*, No. 3,170.

[853] *Ibid.*, No. 3,641. The velocity of a point on the equator of Venus, if Brenner's period of 23h. 57m. were exact, would be 0·28 miles per second; but the displacements due to this rate would be doubled by reflection.

[854] *Novæ Observationes*, p. 92.

[855] *Mém. de l'Ac.*, 1700, p. 296.

[856] *Phil. Trans.*, vol. lxxxiii., p. 201.

[857] Webb, *Cel. Objects*, p. 58.

[858] *Month. Not.*, vol. xlii., p. 111.

[859] *Bull. Ac. de Bruxelles*, t. xliii., p. 22.

[860] *Phil. Trans.*, vol. lxxxii., p. 309; *Aphroditographische Fragmente*, p. 85 (1796).

[861] *Astr. Nach.*, No. 679.

[862] *Month. Not.*, vol. xiv., p. 169.

[863] *Ibid.*, vol. xxiv., p. 25.

[864] *Am. Jour. of Sc.*, vol. xliii., p. 129 (2d ser.); vol. ix., p. 47 (3d ser.).

[865] *Astroph. Jour.*, vol. ix., p. 284.

[866] *Month. Not.*, vol. xxxvi., p. 347.

[867] *Old and New Astronomy*, p. 448.

[868] *Hist. Phys. Astr.*, p. 431.

[869] *Mem. Roy. Astr. Soc.*, vol. xlvii., pp. 77, 84.

[870] *Astr. Reg.*, vol. xiii., p. 132.

[871] *L'Astronomie*, t. ii., p. 27; *Astr. Nach.*, No. 2,021; *Am. Jour. of Sc.*, vol. xxv., p. 430.

[872] *Mem. Spettr. Ital.*, Dicembre, 1882; *Am. Jour. of Sc.*, vol. xxv., p. 328.

[873] *Comptes Rendus*, t. cxvi., p. 288.

[874] Vogel, *Spectra der Planeten*, p. 15.

[875] *Nature*, vol. xix., p. 23.

[876] *Nova Acta Acad. Naturæ Curiosorum*, Bd. x., 239.

[877] *Astr. Jahrbuch*, 1809, p. 164.

[878] *Month Not.*, vol. xliii., p. 331.

[879] *Report Brit. Ass.*, 1873, p. 407. The paper contains a valuable record of observations of the phenomenon.

[880] *Photom. Untersuchungen*, p. 301.

[881] *Bothkamp Beobachtungen*, Heft ii., p. 126.

[882] *Astr. Nach.*, No. 2,818.

[883] *Mémoires de l'Acad. de Bruxelles*, t. xlix., No. 5, 4to; *Astr. Nach.*, No. 2,809; *f.* Schorr, *Der Venusmond*, 1875.

[884] *Phil. Trans.*, 1839, 1841, 1842.

[885] Delaunay objected (*Comptes Rendus*, t. lxvii., p. 65) that the viscosity of the contained liquid (of which Hopkins took no account) would, where the movements were so excessively slow as those of the earth's axis, almost certainly cause it to behave like a solid. Lord Kelvin, however (*Report Brit. Ass.*, 1876, ii., p. 1), considered Hopkins's argument valid as regards the comparatively quick solar semi-annual and lunar fortnightly nutations.

[886] *Phil. Trans.*, cliii., p. 573.

[887] *Report Brit. Ass.*, 1868, p. 494.

[888] *Ibid.*, 1882, p. 474.

[889] Albrecht, *Astr. Nach.*, No. 3,131.

[890] *Astr. Jour.*, Nos. 248, 249.

[891] *Ibid.*, No. 258.

[892] *Month. Not.*, vol. lii., p. 336.

[893] *Astr. Nach.*, No. 3,097; *Phil. Trans.*, vol. clxxxvi., A., p. 469; *Proc. Roy. Soc.*, vol. lix.

[894] See Chandler's searching investigations, *Astr. Jour.*, Nos. 329, 344, 351, 392, 402, 406, 412, 446, 489, 490, 494, 495.

[895] Rees, *Pop. Astr.*, No. 74, 1900.

[896] *Nature*, vol. lxi., p. 447; see also A. V. Bäcklund, *Astr. Nach.*, No. 3,787.

[897] *Trans. Geol. Soc.*, vol. iii. (2d ser.), p. 293.

[898] See his *Treatise on Astronomy*, p. 199 (1833).

[899] *Phil. Mag.*, vol. xxviii. (4th ser.), p. 121.

[900] *Climate and Time*, 1875; *Discussions on Climate and Cosmology*, 1885.

[901] See for a popular account of the theory, Sir R. Ball's *The Cause of an Ice Age*, 1892.

[902] See A. Woeikof, *Phil. Mag.*, vol. xxi., p. 223.

[903] *The Ice Age in North America*, London, 1890.

[904] *Phil. Trans.*, vol. lxviii., p. 783.

[905] *Comptes Rendus*, t. lxxvi., p. 954.

[906] *Potsdam Publ.*, Nos. 22, 23.

[907] *Phil. Trans.*, vol. clxxxii., p. 565; *Adams Prize Essay for 1893.*

[908] *Denkschriften Akad. der Wiss. Wien*, Bd. lxiv.; quoted by Poynting. *Nature*, vol. lxii., p. 404.

[909] *Report on the Geodetic Survey of S. Africa*, 1894.

[910] *Nature*, vol. lxii., p. 622; Hollis, *Observatory*, vol. xxiii., p. 337; Poincaré, *Comptes Rendus*, July 23, 1900.

[911] *Astr. Nach.*, No. 2,228.

[912] Young's *Gen. Astr.*, p. 601.

[913] *Astr. Constants*, p. 195.

[914] The second volume was published at Göttingen in 1802.

[915] *Ueber Rillen auf dem Monde*, p. 13. *Cf. The Moon*, by T. Gwyn Elger, p. 20. W. H. Pickering, *Harvard Annals*, vol. xxxii., p. 249.

[916] *The Moon*, p. 73.

[917] *Selen. Fragm.*, Th. ii., p. 399.

[918] *Astr. Nach.*, No. 263 (1834); *Pop. Vorl.*, pp. 615-620 (1838).

[919] *Outlines of Astr.*, par. 431.

[920] *Month. Not.*, vol. xxv., p. 61.

[921] *Month. Not.*, vol. xxv., p. 264.

[922] *Astroph. Jour.*, vol. vi., p. 422.

[923] *Harvard Annals*, vol. xxxii., p. 81.

[924] *Astr. and Astrophysics*, vol. xi., p. 778.

[925] Neison, *The Moon*, p. 25.

[926] *Knowledge*, vol. xvii., p. 85.

[927] Neison, *The Moon*, p. 104.

[928] The combination of a uniform rotational with an unequal orbital movement causes a slight swaying of the moon's globe, now east, now west, by which we are able to see round the edges of the averted hemisphere. There is also a "parallactic" libration, depending on the earth's rotation; and a species of nodding movement—the "libration in latitude"—is produced by the inclination of the moon's axis to her orbit, and by her changes of position with regard to the terrestrial equator. Altogether, about 2/11 of the *invisible* side come into view.

[929] *Cel. Objects*, p. 58 (4th ed.).

[930] *Astr. Nach.*, No. 1,631.

[931] Cf. Leo Brenner, *Naturwiss. Wochenschrift*, January 13, 1895; *Jour. Brit. Astr. Ass.*, vol. v., pp. 29, 222.

[932] Respighi, *Les Mondes*, t. xiv., p. 294; Huggins, *Month. Not.*, vol. xxvii., p. 298.

[933] Birt, *Ibid.*, p. 95.

[934] *Report Brit. Ass.*, 1872, p. 245.

[935] *Observatory*, vol. xv., p. 250.

[936] *Astr. Reg.*, vol. xvi., p. 265; *Astr. Nach.*, No. 2,275.

[937] Lindsay and Copeland, *Month. Not.*, vol. xxxix., p. 195.

[938] *Observatory*, vols. ii., p. 296; iv., p. 373. N. E. Green (*Astr. Reg.*, vol. xvii., p. 144) concluded the object a mere "spot of colour," dark under oblique light.

[939] Webb, *Cel. Objects*, p. 101.

[940] *Publ. Lick Observatory*, vol. iii., p. 7.

[941] *Ibid.*, p. 21; Mee, *Knowledge*, vol. xviii., p. 135.

[942] *Comptes Rendus*, t. cxxii., p. 967; *Bull. Astr.*, August, 1899; *Ann. Bureau des Long.*, 1898; *Nature*, vols. lii., p. 439; lvi., p. 280; lix., p. 304; lx., p. 491; *Astroph. Jour.* vol. vi., p. 51.

[943] *Comptes Rendus*, t. xxii., p. 541.

[944] *Phil. Trans.*, vol. cxlviii., p. 502.

[945] *Proc. Roy. Soc.*, vol. xvii., p. 443.

[946] *Phil. Trans.*, vol. clxiii., p. 623.

[947] *Trans. R. Dublin Soc.*, vol. iii., p. 321.

[948] *Science*, vol. vii., p. 9.

[949] *Amer. Jour. of Science*, vol. xxxviii., p. 428.

[950] "The Temperature of the Moon," *Memoirs National Acad. of Sciences*, vol. iv., p. 193, 1889.

[951] *Temperature of the Moon*, p. iii.; see also App. ii., p. 206.

[952] *Trans. R. Dublin Soc.*, vol. iv., p. 481, 1891; Rosse, *Proc. Roy. Institution*, May 31, 1895.

[953] *Astroph. Jour.*, vol. viii., pp. 199, 265.

[954] Airy, *Observatory*, vol. iii., p. 420.

[955] *Phil. Trans.*, vol. cxliii., p. 397; *Proc. Roy. Soc.*, vol. vi., p. 321.

[956] *Comptes Rendus*, t. lxi., p. 1023.

[957] Professor Darwin calculated that the heat generated by tidal friction in the course of lengthening the earth's period of rotation from 23 to 24 hours, equalled 23 million times the amount of its present annual loss by cooling. *Nature*, vol. xxxiv., p. 422.

[958] *Sämmtl. Werke* (ed. 1839), Th. vi., pp. 5-12. See also C. J. Monro's useful indications in *Nature*, vol. vii., p. 241.

[959] *Dynamik des Himmels*, p. 40.

[960] Gould's *Astr. Jour.*, vol. iii., p. 138.

[961] *Wash. Obs.* for 1875, vol. xxii., App. ii.

[962] *Comptes Rendus*, t. cxiii., p. 669; *Annuaire*, Paris, 1892.

[963] Newcomb, *Pop. Astr.* (4th ed.), p. 101.

[964] Sir W. Thomson, *Report Brit. Ass.*, 1876, p. 12.

CHAPTER VIII

PLANETS AND SATELLITES—(*continued*)

"The analogy between Mars and the earth is perhaps by far the greatest in the whole solar system." So Herschel wrote in 1783,[965] and so we may safely say to-day, after six score further years of scrutiny. The circumstance lends a particular interest to inquiries into the physical habitudes of our exterior planetary neighbour.

Fontana first caught glimpses, at Naples in 1636 and 1638,[966] of dusky stains on the ruddy disc of Mars. They were next seen by Hooke and Cassini in 1666, and this time with sufficient distinctness to serve as indexes to the planet's rotation, determined by the latter as taking place in a period of twenty-four hours forty minutes.[967] Increased confidence was given to this result through Maraldi's precise verification of it in 1719.[968] Among the spots observed by him, he distinguished two as stable in position, though variable in size. They were of a peculiar character, showing as bright patches round the poles, and had already been noticed during sixty years back. A current conjecture of their snowy nature obtained validity when Herschel connected their fluctuations in extent with the progress of the Martian seasons. The inference of frozen precipitations could scarcely be resisted when once it was clearly perceived that the shining polar zones did actually by turns diminish and grow with the alternations of summer and winter in the corresponding hemisphere.

This, it may be said, was the opening of our acquaintance with the state of things prevailing on the surface of Mars. It was accompanied by a steady assertion, on Herschel's part, of permanence in the dark markings, notwithstanding partial obscurations by clouds and vapours floating in a "considerable but moderate atmosphere." Hence the presumed inhabitants of the planet were inferred to "probably enjoy a situation in many respects similar to ours."[969]

Schröter, on the other hand, went altogether wide of the truth as regards Mars. He held that the surface visible to us is a mere shell of drifting cloud, deriving a certain amount of apparent stability from the influence on evaporation and condensation of subjacent but unseen areographical features;[970] and his opinion prevailed with his contemporaries. It was, however, rejected by Kunowsky in 1822, and finally overthrown by Beer and Mädler's careful studies during five consecutive oppositions, 1830-39. They identified at each the same dark spots, frequently blurred with mists, especially when the local winter prevailed, but fundamentally unchanged.[971] In 1862 Lockyer established a "marvellous agreement" with Beer and Mädler's results of 1830, leaving no doubt as to the complete fixity of the main features, amid "daily, nay, hourly," variations of detail through transits of clouds.[972] On seventeen nights of the same opposition, F. Kaiser of Leyden obtained drawings in which nearly all the markings noted in 1830 at Berlin reappeared, besides spots frequently seen respectively by Arago in 1813, by Herschel in 1783, and one sketched by Huygens in 1672 with a writing-pen in his diary.[973] From these data the Leyden observer arrived at a period of rotation of 24h. 37m. 22·62s., being just one second shorter than that deduced, exclusively from their own observations, by Beer and Mädler. The exactness of this result was practically confirmed by the inquiries of Professor Bakhuyzen of Leyden.[974] Using for a middle term of comparison the disinterred observations of Schröter, with those of Huygens at one, and of Schiaparelli at the other end of an interval of 220 years, he was enabled to show, with something like certainty, that the time of rotation (24h. 37m. 22·735s.) ascribed to Mars by Mr. Proctor[975] in reliance on a drawing executed by Hooke in 1666, was too long by *nearly one-tenth of a second*. The minuteness of the correction indicates the nicety of care employed. Nor employed vainly; for, owing to the comparative antiquity of the records available in this case, an almost infinitesimal error becomes so multiplied by frequent repetition as to produce palpable discrepancies in the positions of the markings at distant dates. Hence Bakhuyzen's period of 24h. 37m. 22·66s. is undoubtedly of a precision unapproached as regards any other heavenly body save the earth itself.

Two facts bearing on the state of things at the surface of Mars were, then, fully acquired to science in or before the year 1862. The first was that of the seasonal fluctuations of the polar spots; the second, that of the general permanence of certain dark gray or greenish patches, perceived with the telescope as standing out from the deep yellow ground of the disc. That these varieties of tint correspond to the real diversities of a terraqueous globe, the "ripe cornfield"[976] sections representing land, the dusky spots and streaks, oceans and straits, has long been the prevalent opinion. Sir J. Herschel in 1830 led the way in ascribing the redness of the planet's light to an inherent peculiarity of soil.[977] Previously it had been assimilated to our sunset glows rather than to our red sandstone formations—set down, that is, to an atmospheric stoppage of blue rays. But the extensive Martian atmosphere, implicitly believed in on the strength of some erroneous observations by Cassini and Römer in the seventeenth century, vanished before the sharp occultation of a small star in Leo, witnessed by Sir James South in 1822;[978] and Dawes's observation in 1865,[979] that the ruddy tinge is deepest near the central parts of the disc, certified its non-atmospheric origin. The absolute whiteness of the polar snow-caps was alleged in support of the same inference by Sir William Huggins in 1867.[980]

All recent operations tend to show that the atmosphere of Mars is much thinner than our own. This was to have been expected *à priori*, since the same proportionate mass of air would on his smaller globe form a relatively sparse covering.[981] Besides, gravity there possesses less than four-tenths its force here, so that this sparser covering would weigh less, and be less condensed, than if it enveloped the earth. Atmospheric pressure would accordingly be of about two and a quarter, instead of fifteen terrestrial pounds per square inch. This corresponds with what the telescope shows us. It is extremely doubtful whether any features of the earth's actual surface could be distinguished by a planetary spectator, however well provided with optical assistance. Professor Langley's inquiries[982] led him to conclude that fully twice as much light is absorbed by our air as had previously been supposed—say 40 per cent. of vertical rays in a clear sky. Of the sixty reaching the earth, less than a quarter would be reflected even from white sandstone; and this quarter would again pay heavy toll in escaping back to space. Thus not more than perhaps ten or twelve out of the original hundred sent by the sun would, under the most favourable circumstances, and from the very centre of the earth's disc, reach the eye of a Martian or lunar observer. The light by which he views our world is, there is little doubt, light reflected from the various strata of our atmosphere, cloud or mist-laden or serene, as the case may be, with an occasional snow-mountain figuring as a permanent white spot.

This consideration at once shows us how much more tenuous the Martian air must be, since it admits of topographical delineations of the Martian globe. The clouds, too, that form in it seem in general to be rather of the nature of ground-mists than of heavy cumulus.[983] Occasionally, indeed, durable and extensive strata become visible. During the latter half of October, 1894, for instance, a region as large as Europe remained apparently cloud-covered. Yet most recent observers are unable to detect the traces of aqueous absorption in the Martian spectrum noted by Huggins in 1867[984] and by Vogel in 1873.[985] Campbell vainly looked for them,[986] visually in 1894, spectrographically in 1896; Keeler was equally unsuccessful;[987] Jewell[988] holds that they could, with present appliances, only be perceived if the atmosphere of Mars were much richer in water-vapour than that of the earth. There can be little doubt, however, that its supply is about the minimum adequate to the needs of a *living*, and perhaps a life-nuturing planet.

The climate of Mars seems to be unexpectedly mild. Its *theoretical* mean temperature, taking into account both distance from the sun and albedo, is 34° C. below freezing.[989] Yet its polar snows are both less extensive and less permanent than those on the earth. The southern white hood, noticed by Schiaparelli in 1877 to have survived the summer only as a small lateral patch, melted completely in 1894. Moreover, Mr. W. H. Pickering observed with astonishment the disappearance, in the course of thirty-three days of June and July, 1892, of 1,600,000 square miles of southern snow.[990] Curiously enough, the initial stage of shrinkage in the white calotte was marked by its division into two unequal parts, as if in obedience to the mysterious principle of duplication governing so many Martian phenomena.[991] Changes of the hues associated respectively with land and water accompanied in lower latitudes, and were thought to be occasioned by floods ensuing upon this rapid antarctic thaw. It is true that scarcity of moisture would account for the scantiness and transitoriness of snowy deposits easily liquefied because thinly spread. But we might expect to see the whole wintry hemisphere, at any rate, frost-bound, since the sun radiates less than half as much heat on Mars as on the earth. Water seems, nevertheless, to remain, as a rule, uncongealed everywhere outside the polar regions. We are at a loss to imagine by what beneficent arrangement the rigorous conditions naturally to be looked for can be modified into a climate which might be found tolerable by creatures constituted like ourselves.

Martian topography may be said to form nowadays a separate sub-department of descriptive astronomy. The amount of detail become legible by close scrutiny on a little disc which, once in fifteen years, attains a maximum of about 1/5000 the area of the full moon, must excite surprise and might provoke incredulity. Spurious discoveries, however, have little chance of holding their own where there are so many competitors quite as ready to dispute as to confirm.

The first really good map of Mars was constructed in 1869 by Proctor from drawings by Dawes. Kaiser of Leyden followed in 1872 with a representation founded upon data of his own providing in 1862-64; and Terby, in his valuable *Aréographie*, presented to the Brussels Academy in 1873[992] a careful discussion of all important observations from the time of Fontana downwards, thus virtually adding to knowledge by summarising and digesting it. The memorable opposition of September 5, 1877, marked a fresh epoch in the study of Mars. While executing a trigonometrical survey (the first attempted) of the disc, then of the unusual size of 25′ across, G. V. Schiaparelli, director of the Milan Observatory, detected a novel and curious feature. What had been taken for Martian continents were found to be, in point of fact, agglomerations of islands, separated from each other by a network of so-called "canals" (more properly *channels*).[993] These are obviously extensions of the "seas," originating and terminating in them, and sharing their gray-green hue, but running sometimes to a length of three or four thousand miles in a straight line, and preserving throughout a nearly uniform breadth of about sixty miles. Further inquiries have fully substantiated the discovery made at the Brera Observatory. The "canals" of Mars are an actually existent and permanent phenomenon. An examination of the drawings in his possession showed M. Terby that they had been seen, though not distinctively recognised, by Dawes, Secchi, and Holden; several were independently traced out by Burton at the opposition of 1879; all were recovered by Schiaparelli himself in 1879 and 1881-82; and their indefinite multiplication resulted from Lovell's observations in 1894 and 1896.

When the planet culminated at midnight, and was therefore in opposition, December 26, 1881, its distance was greater, and its apparent diameter less than in 1877, in the proportion of sixteen to twenty-five. Its atmosphere was, however, more transparent, and ours of less impediment to northern observers, the object of scrutiny standing considerably higher in northern skies. Never before, at any rate, had the true aspect of Mars come out so clearly as at Milan, with the 8-3/4-inch Merz refractor of the observatory, between December, 1881, and February, 1882. The canals were all again there, but this time they were—in as many as twenty cases—*seen in duplicate*. That is to say, a twin-canal ran parallel to the original one at an interval of 200 to 400 miles.[994]

We are here brought face to face with an apparently insoluble enigma. Schiaparelli regards the "germination" of his canals as a periodical phenomenon depending on the Martian seasons. It is, assuredly, not an illusory one, since it was plainly apparent, during the opposition of 1886, to MM. Perrotin and Thollon at Nice,[995] and to the former, using the new 30-inch refractor of that observatory, in 1888; Mr. A. Stanley Williams, with the help of only a 6-1/2-inch reflector, distinctly perceived in 1890 seven of the duplicate objects noted at Milan,[996] and the Lick observations, both of 1890 and of 1892, together with the drawings made at Flagstaff and Mexico during the last favourable oppositions of the nineteenth century, brought unequivocal confirmation to the accuracy of Schiaparelli's impressions.[997] Various conjectures have been hazarded in explanation of this bizarre appearance. The difficulty of conceiving a physical reality corresponding to it has suggested recourse to an optical rationale. Proctor regarded it as an effect of diffraction;[998] Stanislas Meunier, of oblique reflection from overlying mist-banks;[999] Flammarion considers it possible that companion-canals might, under special circumstances, be evoked by refraction as a kind of mirage.[1000] But none of these speculations are really admissible, when all the facts are taken into account. The view that the canals of Mars are vast rifts due to the cooling of the globe, is recommended by the circumstance that they tend to follow great circles; nevertheless, it would break down if, as Schiaparelli holds, the fluctuations in their visibility depend upon actual obliterations and re-emergencies. Fantastic though the theory of their artificial origin appear, it is held by serious astronomers. Its vogue is largely due to Mr. Lowell's ingenious advocacy. He considers the Martian globe to be everywhere intersected by an elaborate system of irrigation-works, rendered necessary by a perennial water-famine, relieved periodically by the melting of the polar snows. Nor does he admit the existence of oceans, or lakes. What have been taken for such are really tracts covered with vegetation, the bright areas intermixed with them representing sandy deserts. And it is noteworthy in this connection that Professor Barnard obtained in 1894,[1001] with the great Lick refractor, "suggestive and impressive views" disclosing details of light and shade on the gray-green patches so intricate and minute as almost to preclude the supposition of their aqueous nature.

The closeness of the terrestrial analogy has thus of late been much impaired. Even if the surface of Mars be composed of land and water, their distribution must be of a completely original type. The interlacing everywhere of continents with arms of the sea (if that be the correct interpretation of the visual effects) implies that their levels scarcely differ;[1002] and Schiaparelli carries most observers with him in holding that their outlines are not absolutely constant, encroachments of dusky upon bright tints suggesting extensive inundations.[1003] The late N. E. Green's observations at Madeira in 1877 indicated, on the other hand, a rugged south polar region. The contour of the snow-cap not only appeared indented, as if by valleys and promontories, but brilliant points were discerned outside the white area, attributed to isolated snow-peaks.[1004] Still more elevated, if similarly explained, must be the "ice island" first seen in a comparatively low latitude by Dawes in January, 1865.

On August 4, 1892, Mars stood opposite to the sun at a distance of only 34,865,000 miles from the earth. In point of vicinity, then, its situation was scarcely less favourable than in 1877. The low altitude of the planet, however, practically neutralised this advantage for northern observers, and public expectation, which had been raised to the highest pitch by the announcements of sensation-mongers, was somewhat disappointed at the "meagreness" of the news authentically received from Mars. Valuable series of observations were, nevertheless, made at Lick and Arequipa; and they unite in testifying to the genuine prevalence of surface-variability, especially in certain regions of intermediate tint, and perhaps of the "crude consistence" of "boggy Syrtes, neither sea, nor good dry land." Professor Holden insisted on the "enormous difficulties in the way of completely explaining the recorded phenomena by terrestrial analogies";[1005] Mr. W. H. Pickering spoke of "conspicuous and startling changes." They, however, merely overlaid, and partially disguised, a general stability. Among the novelties detected by Mr. Pickering were a number of "lakes," or "oases" (in Lowell's phraseology), under the aspect of black dots at the junctions of two or more canals;[1006] and he, no less than the Lick astronomers and M. Perrotin at Nice,[1007] observed brilliant clouds projecting beyond the terminator, or above the limb, while carried round by the planet's rotation. They seemed to float at an altitude of at least twenty miles, or about four times the height of terrestrial cirrus; but this was not wonderful, considering the low power of gravity acting upon them. Great capital was made in the journalistic interest out of these imaginary signals from intelligent Martians, desirous of opening communications with (to them) problematical terrestrial beings. Similar effects had, however, been seen before by Mr. Knobel in 1873, by M. Terby in 1888, and at the Lick Observatory in 1890; and they were discerned again with particular distinctness by Professor Hussey at Lick, August 27, 1896.[1008]

The first photograph of Mars was taken by Gould at Cordoba in 1879. Little real service in planetary delineation has, it is true, been so far rendered by the art, yet one achievement must be recorded to its credit. A set of photographs obtained by Mr. W. H. Pickering on Wilson's Peak, California, April 9, 1890, showed the southern polar cap of Mars as of moderate dimensions, but with a large dim adjacent area. Twenty-four hours later, on a corresponding set, the dim area was brilliantly white. The polar cap had become enlarged in the interim, apparently through a wide-spreading snow-fall, by the annexation of a territory equal to that of the United States. The season was towards the close of winter in Mars. Never until then had the process of glacial extension been actually (it might be said) superintended in that distant globe.

Mars was gratuitously supplied with a pair of satellites long before he was found actually to possess them. Kepler interpreted Galileo's anagram of the "triple" Saturn in this sense; they were perceived by Micromégas on his long voyage through space; and the Laputan astronomers had even arrived at a knowledge, curiously accurate under the circumstances, of their distances and periods. But terrestrial observers could see nothing of them until the night of August 11, 1877. The planet was then within one month of its second nearest approach to the earth during the last century; and in 1845 the Washington 26-inch refractor was not in existence.[1009] Professor Asaph Hall, accordingly, determined to turn the conjecture to account for an exhaustive inquiry into the surroundings of Mars. Keeping his glaring disc just outside the field of view, a minute attendant speck of light was "glimpsed" August 11. Bad weather, however, intervened, and it was not until the 16th that it was ascertained to be what it appeared—a satellite. On the following evening a second, still nearer to the primary, was discovered, which, by the bewildering rapidity of its passages hither and thither, produced at first the effect of quite a crowd of little moons.[1010]

Both these delicate objects have since been repeatedly observed, both in Europe and America, even with comparatively small instruments. At the opposition of 1884, indeed, the distance of the planet was too great to permit of the detection of both elsewhere than at Washington. But the Lick equatoreal showed them, July 18, 1888, when their brightness was only 0·12 its amount at the time of their discovery; so that they can now be followed for a considerable time before and after the least favourable oppositions.

The names chosen for them were taken from the Iliad, where "Deimos" and "Phobos" (Fear and Panic) are represented as the companions in battle of Ares. In several respects, they are interesting and remarkable bodies. As to size, they may be said to stand midway between meteorites and satellites. From careful photometric measures executed at Harvard in 1877 and 1879, Professor Pickering concluded their diameters to be respectively six and seven miles.[1011] This is on the assumption that they reflect the same proportion of the light incident upon them that their primary does. But it may very well be that they are less reflective, in which case they would be more extensive. The albedo of Mars is put by Müller at 0·27; his surface, in other words, returns 27 per cent. of the rays striking it. If we put the albedo of his satellites equal to that of our moon, 0·17, their diameters will be increased from 6 and 7 to 7-1/2 and 9 miles, Phobos, the inner one, being the larger. Mr. Lowell, however, formed a considerably larger estimate of their dimensions.[1012] It is interesting to note that Deimos, according to Professor Pickering's very distinct perception, does not share the reddish tint of Mars.

Deimos completes its nearly circular revolutions in thirty hours eighteen minutes, at a distance from the surface of its ruling body of 12,500 miles; Phobos traverses an elliptical orbit[1013] in seven hours thirty-nine minutes twenty-two seconds, at a distance of only 3,760 miles. This is the only known instance of a satellite circulating faster than its primary rotates, and is a circumstance of some importance as regards theories of planetary development. To a Martian spectator the curious effect would ensue of a celestial object, seemingly exempt from the general motion of the sphere, rising in the west, setting in the east, and culminating twice, or even thrice a day; which, moreover, in latitudes above 69° north or south, would be permanently and altogether hidden by the intervening curvature of the globe.

The detection of new members of the solar system has come to be one of the most ordinary of astronomical events. Since 1846 no single year has passed without bringing its tribute of asteroidal discovery. In the last of the seventies alone, a full score of miniature planets were distinguished from the thronging stars amid which they seem to move; 1875 brought seventeen such recognitions; their number touched a minimum of one in 1881; it rose in 1882, and again in 1886, to eleven; dropped to six in 1889, and sprang up with the aid of photography to twenty-seven in 1892. That high level has since, on an average, been maintained; and on January 1, 1902, nearly 500 asteroids were recognised as revolving between the orbits of Mars and Jupiter. Of these, considerably more than one hundred are claimed by one investigator alone—Dr. Max Wolf of Heidelburg; M. Charlois of Nice comes second with 102; while among the earlier observers Palisa of Vienna contributed 86, and C. H. F. Peters of Clinton (N. Y.), whose varied and useful career terminated July 19, 1890, 52 to the grand total.

The construction by Chacornac and his successors at Paris, and more recently by Peters at Clinton, of ecliptical charts showing all stars down to the thirteenth and fourteenth magnitudes respectively, rendered the picking out of moving objects above that brightness a mere question of time and diligence. Both, however, are vastly economised by the photographic method. Tedious comparisons of the sky with charts are no longer needed for the identification of unrecorded, because simulated stars. Planetary bodies declare themselves by appearing upon the plate, not in circular, but in linear form. Their motion converts their images into trails, long or short according to the time of exposure. The first asteroid (No. 323) thus detected was by Max Wolf, December 22, 1891.[1014] Eighteen others were similarly discovered in 1892, by the same skilful operator; and ten more through Charlois's adoption at Nice of the novel plan now in exclusive use for picking up errant light-specks. Far more onerous than the task of their discovery is that of keeping them in view once discovered—of tracking out their paths, fixing their places, and calculating the disturbing effects upon them of the mighty Jovian mass. These complex operations have come to be centralised at Berlin under the superintendence of Professor Tietjen, and their results are given to the public through the medium of the *Berliner Astronomisches Jahrbuch*.

The *cui bono?* however, began to be agitated. Was it worth while to maintain a staff of astronomers for the sole purpose of keeping hold over the identity of the innumerable component particles of a cosmical ring? The prospect, indeed, of all but a select few of the asteroids being thrown back by their contemptuous captors into the sea of space seemed so imminent that Professor Watson provided by will against the dereliction of the twenty-two discovered by himself. But the fortunes of the whole family improved through the distinction obtained by one of them. On August 14, 1898, the trail of a rapidly-moving, star-like object of the eleventh magnitude imprinted itself on a plate exposed by Herr Witt at the Urania Observatory, Berlin. Its originator proved to be unique among asteroids. "Eros" is, in sober fact,

> ‘one of those mysterious stars Which hide themselves between the Earth and Mars,’

divined or imagined by Shelley.[1015] True, several of its congeners invade the Martian sphere at intervals; but the proper habitat of Eros is within that limit, although its excursions transcend it. In other words, its mean distance from the sun is about 135, as compared with the Martian distance of 141 million miles. Further, its orbit being so fortunately circumstanced as to bring it once in sixty-seven years within some 15 millions of miles of the earth, it is of extraordinary value to celestial surveyors. The calculation of its movements was much facilitated by detections, through a retrospective search,[1016] of many of its linear images among the star-dots on the Harvard plates.[1017] The little body—which can scarcely be more than twenty miles in diameter—shows peculiarities of behaviour as well as of position. Dr. von Oppolzer, in February, 1901,[1018] announced it to be extensively and rapidly variable. Once in 2 hours 38 minutes it lost about three-fourths of its light,[1019] but these fluctuations quickly diminished in range, and in the beginning of May ceased altogether.[1020] Evidently, then, they depend upon the situation of the asteroid relatively to ourselves; and, so far, events lent countenance to M. André‘s eclipse hypothesis, since mutual occultations of the supposed planetary twins could only take place when the plane of their revolutions passed through the earth, and this condition would be transitory. Yet the recognition in Eros of an “Algol asteroid” seems on other grounds inadmissible;[1021] nor until the phenomenon is conspicuously renewed—as it probably will be at the opposition of 1903—can there be much hope of finding its appropriate rationale.

The crowd of orbits disclosed by asteroidal detections invites attentive study. D’Arrest remarked in 1851,[1022] when only thirteen minor planets were known, that supposing their paths to be represented by solid hoops, not one of the thirteen could be lifted from its place without bringing the others with it. The complexity of interwoven tracks thus illustrated has grown almost in the numerical proportion of discovery. Yet no two actually intersect, because no two lie exactly in the same plane, so that the chances of collision are at present *nil*. There is only one case, indeed, in which it seems to be eventually possible. M. Lespiault has pointed out that the curves traversed by “Fidés” and “Maïa” approach so closely that a time may arrive when the bodies in question will either coalesce or unite to form a binary system.[1023]

The maze threaded by the 500 asteroids contrasts singularly with the harmoniously ordered and rhythmically separated orbits of the larger planets. Yet the seeming confusion is not without a plan.

The established rules of our system are far from being totally disregarded by its minor members. The orbit of Pallas, with its inclination of 34° 42′, touches the limit of departure from the ecliptic level; the average obliquity of the asteroidal paths is somewhat less than that of the sun’s equator;[1024] their mean eccentricity is below that of the curve traced out by Mercury, and all without exception are pursued in the planetary direction—from west to east.

The zone in which these small bodies travel is about three times as wide as the interval separating the earth from the sun. It extends perilously near to Jupiter, and dovetails into the sphere of Mars.

Their distribution is very unequal. They are most densely congregated about the place where a single planet ought, by Bode's Law, to revolve; it may indeed be said that only stragglers from the main body are found more than fifty million miles within or without a mean distance from the sun 2·8 times that of the earth. Significant gaps, too, occur where some force prohibitive of their presence would seem to be at work. The probable nature of that force was suggested by the late Professor Kirkwood, first in 1866, when the number of known asteroids was only eighty-eight, and again with more confidence in 1876, from the study of a list then run up to 172.[1025] It appears that these bare spaces are found just where a revolving body would have a period connected by a simple relation with that of Jupiter. It would perform two or three circuits to his one, five to his two, nine to his five, and so on. Kirkwood's inference was that the gaps in question were cleared of asteroids by the attractive influence of Jupiter. For disturbances recurring time after time—owing to commensurability of periods—nearly at the same part of the orbit, would have accumulated until the shape of that orbit was notably changed. The body thus displaced would have come in contact with other cosmical particles of the same family with itself—then, it may be assumed, more evenly scattered than now—would have coalesced with them, and permanently left its original track. In this way the regions of maximum perturbation would gradually have become denuded of their occupants.

We can scarcely doubt that this law of commensurability has largely influenced the present distribution of the asteroids. But its effects must have been produced while they were still in an unformed, perhaps a nebular condition. In a system giving room for considerable modification through disturbance, the recurrence of conjunctions with a dominating mass at the same orbital point need not involve instability.[1026] On the whole, the correspondence of facts with Kirkwood's hypothesis has not been impaired by their more copious collection.[1027] Some chasms of secondary importance have indeed been bridged; but the principal stand out more conspicuously through the denser scattering of orbits near their margins. Nor is it doubtful that the influence of Jupiter in some way produced them. M. de Freycinet's study of the problem they present[1028] has, however, led him to the conclusion that they existed *ab origine*, thus testifying rather to the preventive than to the perturbing power of the giant planet.

The existence, too, of numerous asteroidal pairs travelling in approximately coincident tracks, must date from a remote antiquity. They result, Professor Kirkwood[1029] believed, from the divellent action of Jupiter upon embryo pigmy planets, just as comets moving in pursuit of one another are a consequence of the sundering influence of the sun.

Leverrier fixed, in 1853,[1030] one-fourth of the earth's mass as the outside limit for the combined masses of all the bodies circulating between Mars and Jupiter; but it is far from probable that this maximum is at all nearly approached. M. Berberich[1031] held that the moon would more than outweigh the whole of them, a million of the lesser bodies shining like stars of the twelfth magnitude being needed, according to his judgment, to constitute her mass. And M. Niesten estimated that the whole of the 216 asteroids discovered up to August, 1880, amounted in *volume* to only 1/4000th of our globe,[1032] and we may safely add—since they are tolerably certain to be lighter, bulk for bulk, than the earth—that their proportionate *mass* is smaller still. A fairly concordant result was published in 1895 by Mr. B. M. Roszel.[1033] He found that the lunar globe probably contains forty times, the terrestrial globe 3,240 times the quantity of matter parcelled out among the first 311 minor planets. The actual size of a few of them may now be said to be known. Professor Pickering, from determinations of light-intensity, assigned to Vesta a diameter of 319 miles, to Pallas 167, to Juno 94, down to twelve and fourteen for the smaller members of the group.[1034] An albedo equal to that of Mars was assumed as the basis of the calculation. Moreover, Professor G. Müller[1035] of Potsdam examined photometrically the phases of seven among them, of which four—namely, Vesta, Iris, Massalia, and Amphitrite—were found to conform precisely to the behaviour of Mars as regards light-change from position, while Ceres, Pallas, and Irene varied after the manner of the moon and Mercury. The first group were hence inferred to resemble Mars in physical constitution, nature of atmosphere, and reflective capacity; the second to be moon-like bodies.

Finally, Professor Barnard, directly measuring with the Yerkes refractor the minute discs presented by the original quartette, obtained the following authentic data concerning them:[1036] Diameter of Ceres, 477 miles, albedo = 0·18; diameter of Pallas, 304 miles, albedo = 0·23; diameter of Vesta, 239 miles, albedo = 0·74; diameter of Juno, 120 miles, albedo = 0·45. Thus, the rank of premier asteroid proves to belong to Ceres, and to have been erroneously assigned to Vesta in consequence of its deceptive brilliancy. What kind of surface this indicates, it is hard to say. The dazzling whiteness of snow can hardly be attributed to bare rock; yet the dynamical theory of gases—as Dr. Johnstone Stoney pointed out in 1867[1037]—prohibits the supposition that bodies of insignificant gravitative power can possess aerial envelopes. Even our moon, it is calculated, could not permanently hold back the particles of oxygen, nitrogen, or water-gas from escaping into infinite space; still less, a globe one thousand times smaller. Vogel's suspicion of an air-line in the spectrum of Vesta[1038] has, accordingly, not been confirmed.

Crossing the zone of asteroids on our journey outward from the sun, we meet with a group of bodies widely different from the "inferior" or terrestrial planets. Their gigantic size, low specific gravity, and rapid rotation, obviously from the first threw the "superior" planets into a class apart; and modern research has added qualities still more significant of a dissimilar physical constitution. Jupiter, a huge globe 86,000 miles in diameter, stands pre-eminent among them. He is, however, only *primus inter pares*; all the wider inferences regarding his condition may be extended, with little risk of error, to his fellows; and inferences in his case rest on surer grounds than in the case of the others, from the advantages offered for telescopic scrutiny by his comparative nearness.

Now the characteristic modern discovery concerning Jupiter is that he is a body midway between the solar and terrestrial stages of cosmical existence—a decaying sun or a developing earth, as we choose to put it—whose vast unexpended stores of internal heat are mainly, if not solely, efficient in producing the interior agitations betrayed by the changing features of his visible disc. This view, impressed upon modern readers by Mr. Proctor's popular works, was anticipated in the last century. Buffon wrote in his *Époques de la Nature* (1778):[1039]—"La surface de Jupiter est, comme l'on sait, sujette à des changemens sensibles, qui semblent indiquer que cette grosse planète est encore dans un état d'inconstance et de bouillonnement."

Primitive incandescence, attendant, in his fantastic view, on planetary origin by cometary impacts with the sun, combined, he concluded, with vast bulk to bring about this result. Jupiter has not yet had time to cool. Kant thought similarly in 1785;[1040] but the idea did not commend itself to the astronomers of the time, and dropped out of sight until Mr. Nasmyth arrived at it afresh in 1853.[1041] Even still, however, terrestrial analogies held their ground. The dark belts running parallel to the equator, first seen at Naples in 1630, continued to be associated—as Herschel had associated them in 1781—with Jovian trade-winds, in raising which the deficient power of the sun was supposed to be compensated by added swiftness of rotation. But opinion was not permitted to halt here.

In 1860 G. P. Bond of Cambridge (U.S.) derived some remarkable indications from experiments on the light of Jupiter.[1042] They showed that fourteen times more of the photographic rays striking it are reflected by the planet than by our moon, and that, unlike the moon, which sends its densest rays from the margin, Jupiter is brightest near the centre. But the most perplexing part of his results was that Jupiter actually seemed to give out more light than he received. Bond, however, rightly considered his data too uncertain for the support of so bold an assumption as that of original luminosity, and, even if the presence of native light were proved, thought that it might emanate from auroral clouds of the terrestrial kind. The conception of a sun-like planet was still a remote, and seemed an extravagant one.

Only since it was adopted and enforced by Zöllner in 1865,[1043] can it be regarded as permanently acquired to science. The rapid changes in the cloud-belts both of Jupiter and Saturn, he remarked, attest a high internal temperature. For we know that all atmospheric movements on the earth are sun-heat transformed into motion. But sun-heat at the distance of Jupiter possesses but 1/27, at that of Saturn 1/100 of its force here. The large amount of energy, then, obviously exerted in those remote firmaments must have some other source, to be found nowhere else than in their own active and all-pervading fires, not yet banked in with a thick solid crust.

The same acute investigator dwelt, in 1871,[1044] on the similarity between the modes of rotation of the great planets and of the sun, applying the same principles of explanation to each case. The fact of this similarity is undoubted. Cassini[1045] and Schröter both noticed that markings on Jupiter travelled quicker the nearer they were to his equator; and Cassini even hinted at their possible assimilation to sun-spots.[1046] It is now well ascertained that, as a rule (not without exceptions), equatorial spots give a period some 5-1/2 minutes shorter than those in latitudes of about 30°. But, as Mr. Denning has pointed out,[1047] no single period will satisfy the observations either of different markings at the same epoch, or of the same markings at different epochs. Accelerations and retardations, depending upon processes of growth or change, take place in very much the same kind of way as in solar maculæ, inevitably suggesting similarity of origin.

The interesting query as to Jupiter's surface incandescence has been studied since Bond's time with the aid of all the appliances furnished to physical inquirers by modern inventiveness, yet without bringing to it a categorical reply. Zöllner in 1865, Müller in 1893, estimated his albedo at 0·62 and 0·75 respectively, that of fresh-fallen snow being 0·78, and of white paper 0·70.[1048] But the disc of Jupiter is by no means purely white. The general ground is tinged with ochre; the polar zones are leaden or fawn coloured; large spaces are at times stained or suffused with chocolate-browns and rosy hues. It is occasionally seen ruled from pole to pole with dusky bars, and is never wholly free from obscure markings. The reflection, then, by it, as a whole, of about 70 per cent. of the rays impinging upon it, might well suggest some original reinforcement.

Nevertheless, the spectroscope gives little countenance to the supposition of any considerable permanent light-emission. The spectrum of Jupiter, as examined by Huggins, 1862-64, and by Vogel, 1871-73, shows the familiar Fraunhofer rays belonging to reflected sunlight. But it also shows lines of native absorption.

Some of these are identical with those produced by the action of our own atmosphere, especially one or more groups due to aqueous vapours; others are of unknown origin; and it is remarkable that one among the latter—a strong band in the red—agrees in position with a dark line in the spectra of some ruddy stars.[1049] There is, besides, a general absorption of blue rays, intensified—as Le Sueur observed at Melbourne in 1869[1050]—in the dusky markings, evidently through an increase of depth in the atmospheric strata traversed by the light proceeding from them.

All these observations, however (setting aside the stellar line as of doubtful significance), point to a cool planetary atmosphere. One spectrograph, it is true, taken by Dr. Henry

Draper, September 27, 1879,[1051] seemed to attest the action of intrinsic light; but the peculiarity was referred by Dr. Vogel, with convincing clearness, to a flaw in the film.[1052] So far, then, native emissions from any part of Jupiter's diversified surface have not been detected; and, indeed, the blackness of the shadows cast by his satellites on his disc sufficiently proves that he sends out virtually none but reflected light.[1053] This conclusion, however, by no means invalidates that of his high internal temperature.

The curious phenomena attending Jovian satellite-transits may be explained, partly as effects of contrast, partly as due to temporary obscurations of the small discs projected on the large disc of Jupiter. At their first entry upon its marginal parts, which are several times less luminous than those near the centre, they invariably show as bright spots, then usually vanish as the background gains lustre, to reappear, after crossing the disc, thrown into relief, as before, against the dusky limb. But instances are not rare, more especially of the third and fourth satellites standing out, during the entire middle part of their course, in such inky darkness as to be mistaken for their own shadows. The earliest witness of a "black transit" was Cassini, September 2, 1665; Römer in 1677, and Maraldi in 1707 and 1713, made similar observations, which have been multiplied in recent years. In some cases the process of darkening has been visibly attended by the formation, or emergence into view, of spots on the transiting body, as noted by the two Bonds at Harvard, March 18, 1848.[1054] The third satellite was seen by Dawes, half dark, half bright, when crossing Jupiter's disc, August 21, 1867;[1055] one-third dark by Davidson of California, January 15, 1884, under the same circumstances;[1056] and unmistakably spotted, both on and off the planet, by Schröter, Secchi, Dawes, and Lassell.

The first satellite sometimes looks dusky, but never absolutely black, in travelling over the disc of Jupiter. The second appears uniformly white—a circumstance attributed by Dr. Spitta[1057] to its high albedo. The singularly different aspects, even during successive transits, of the third and fourth satellites, are connected by Professor Holden[1058] with the varied luminosity of the segments of the planetary surface they are projected upon, and W. H. Pickering inclines to the same opinion; but fluctuations in their own brightness[1059] may be a concurrent cause. Herschel concluded in 1797 that, like our moon, they always turn the same face towards their primary, and as regards the outer satellite, Engelmann's researches in 1871, and C. E. Burton's in 1873, made this almost certain; while both for the third and fourth Jovian moons it was completely assured by W. H. Pickering's and A. E. Douglass's observations at Arequipa in 1892,[1060] and at Flagstaff in 1894-95.[1061] Strangely enough, however, the interior members of the system have preserved a relatively swift rotation, notwithstanding the enormous checking influence upon it of Jove-raised tides.

All the satellites are stated, on good authority, to be more or less egg-shaped. On September 8, 1890, Barnard saw the first elongated and bisected by a bright equatorial belt, during one of its dark transits;[1062] and his observation, repeated August 3, 1891, was completely verified by Schaeberle and Campbell, who ascertained, moreover, that the longer axis of the prolate body was directed towards Jupiter's centre.[1063] The ellipticity of its companions was determined by Pickering and Douglass; indeed, that of No. 3 had long previously been noticed by Secchi.[1064] No. 3 also shows equatorial stripes, perceived in 1891 by Schaeberle and Campbell,[1065] and evident later to Pickering and Douglass;[1066] nor need we hesitate to admit as authentic their records of similar, though less conspicuous markings on the other satellites. A constitution analogous to that of Jupiter himself was thus unexpectedly suggested; and Vogel's detection of lines—or traces of lines—in their spectra, agreeing with absorption-rays derived from their primary, lends support to the conjecture that they possess gaseous envelopes similar to his.

The system of Jupiter, as it was discovered by Galileo, and investigated by Laplace, appeared in its outward aspect so symmetrical, and displayed in its inner mechanism such harmonious dynamical relations, that it might well have been deemed complete. Nevertheless, a new member has been added to it. Near midnight on September 9, 1892, Professor Barnard discerned with the Lick 36-inch "a tiny speck of light," closely following the planet.[1067] He instantly divined its nature, watched its hurried disappearance in the adjacent glare, and made sure of the reality of his discovery on the ensuing night. It was a delicate business throughout, the Liliputian luminary subsiding into invisibility before the slightest glint of Jovian light, and tarrying, only for brief intervals, far enough from the disc to admit of its exclusion by means of an occulting plate. The new satellite is estimated to be of the thirteenth stellar magnitude, and, if equally reflective of light with its next neighbour, Io (satellite No. 1), its diameter must be about one hundred miles. It revolves at a distance of 112,500 miles from Jupiter's centre, and of 68,000 from his bulging equatorial surface. Its period of 11h. 57m. 23s. is just two hours longer than Jupiter's period of rotation, so that Phobos still remains a unique example of a secondary body revolving faster than its primary rotates. Jupiter's innermost moon conforms in its motions strictly, indeed inevitably, to the plane of his equatorial protuberance, following, however, a sensibly elliptical path the major axis of which is in rapid revolution.[1068] Its very insignificance raises the suspicion that it may not prove solitary. Possibly it belongs to a zone peopled by asteroidal satellites. More than fifteen thousand such small bodies could be furnished out of the materials of a single full-sized satellite spoiled in the making. But we must be content for the present to register the fact without seeking to penetrate the meaning of its existence. Very high and very fine telescopic power is needed for its perception. Outside the United States, it has been very little observed. The only instruments in this country successfully employed for its detection are, we believe, Dr. Common's 5-foot reflector and Mr. Newall's 25-inch refractor.

In the course of his observations on Jupiter at Brussels in 1878, M. Niesten was struck with a rosy cloud attached to a whitish zone beneath the dark southern equatorial band.[1069] Its size was enormous. At the distance of Jupiter, its measured dimensions of 13′ by 3′ implied a real extension in longitude of 30,000, in latitude of something short of 7,000 miles. The earliest record of its appearance seems to be by Professor Pritchett, director of the Morrison Observatory (U.S.), who figured and described it July 9, 1878.[1070] It was again delineated August 9, by Tempel at Florence.[1071] In the following year it attracted the wonder and attention of almost every possessor of a telescope. Its colour had by that time deepened into a full brick-red, and was set off by contrast with a white equatorial spot of unusual brilliancy. During three ensuing years these remarkable objects continued to offer a visible and striking illustration of the compound nature of the planet's rotation. The red spot completed a circuit in nine hours fifty-five minutes thirty-six seconds; the white spot in about five and a half minutes less. Their *relative* motion was thus no less than 260 miles an hour, bringing them together in the same meridian at intervals of forty-four days ten hours forty-two minutes. Neither, however, preserved continuously the same uniform rate of travel. The period of each had lengthened by some seconds in 1883, while sudden displacements, associated with the recovery of lustre after recurrent fadings, were observed in the position of the white spot,[1072] recalling the leap forward of a reviving sun-spot. Just the opposite effect attended the rekindling of the companion object. While semi-extinct, in 1882-84, it lost little motion; but a fresh access of retardation was observed by Professor Young[1073] in connection with its brightening in 1886. This suggests very strongly that the red spot is *fed from below*. A shining aureola of "faculæ," described by Bredichin at Moscow, and by Lohse at Potsdam, as encircling it in September, 1879,[1074] was held to strengthen the solar analogy.

The conspicuous visibility of this astonishing object lasted three years. When the planet returned to opposition in 1882-83, it had faded so considerably that Riccò's uncertain glimpse of it at Palermo, May 31, 1883, was expected to be the last. It had, nevertheless, begun to recover in December, and presented to Mr. Denning in the beginning of 1886 much the same aspect as in October, 1882.[1075] Observed by him in an intermediate stage, February 25, 1885, when "a mere skeleton of its former self," it bore a striking likeness to an "elliptical ring" descried in the same latitude by Mr. Gledhill in 1869-70. This, indeed, might be called the preliminary sketch for the famous object brought to perfection ten years later, but which Mr. H. C. Russell of Sydney saw and drew still unfinished in June, 1876,[1076] before it had separated from its matrix, the dusky south tropical belt. In earlier times, too, a marking "at once fixed and transient" had been repeatedly perceived attached to the southernmost of the central belts. It gave Cassini in 1665 a rotation-period of nine hours fifty-six minutes,[1077] reappeared and vanished eight times during the next forty-three years, and was last seen by Maraldi in 1713. It was, however, very much smaller than the recent object, and showed no unusual colour.[1078]

The assiduous observations made on the "Great Red Spot" by Mr. Denning at Bristol and by Professor Hough at Chicago afforded grounds only for negative conclusions as to its nature. It certainly did *not* represent the outpourings of a Jovian volcano; it was in no sense attached to the Jovian soil—if the phrase have any application to that planet; it was *not* a mere disclosure of a glowing mass elsewhere seethed over by rolling vapours. It was, indeed, certainly not self-luminous, a satellite projected upon it in transit having been seen to show as bright as upon the dusky equatorial bands. A fundamental objection to all three hypotheses is that the rotation of the spot was variable. It did not then ride at anchor, but floated free. Some held that its surface was depressed below the average cloud-level, and that the cavity was filled with vapours. Professor Wilson, on the other hand, observing with the 16-inch equatorial of the Goodsell Observatory in Minnesota, received a persistent impression of the object "being at a higher level than the other markings."[1079] A crucial experiment on this point was proposed by Mr. Stanley Williams in 1890.[1080] A dark spot moving faster along the same parallel was timed to overtake the red spot towards the end of July. A unique opportunity hence appeared to be at hand of determining the relative vertical depths of the two formations, one of which must inevitably, it was thought, pass above the other. No forecast included a third alternative, which was nevertheless adopted by the dark spot. It evaded the obstacle in its path by skirting round its southern edge.[1081] Nothing, then, was gained by the conjunction, beyond an additional proof of the singular repellent influence exerted by the red spot over the markings in its vicinity. It has, for example, gradually carved out a deep bay for its accommodation in the gray belt just north of it. The effect was not at first steadily present. A premonitory excavation was drawn by Schwabe at Dessau, September 5, 1831, and again by Trouvelot, Barnard, and Elvins in 1879; yet there was no sign of it in the following year. Its development can be traced in Dr. Boeddicker's beautiful delineations of Jupiter, made with the Parsonstown 3-foot reflector, from 1881 to 1886.[1082] They record the belt as straight in 1881, but as strongly indented from January, 1883; and the cavity now promises to outlast the spot. So long as it survives, however, the forces at work in the spot can have lost little of their activity. For it must be remembered that the belt has a shorter rotation-period than the red spot, which, accordingly (as Mr. Elvins of Toronto has pointed out), breasts and diverts, by its interior energy, a current of flowing matter, ever ready to fill up its natural bed, and override the barrier of obstruction.

The famous spot was described by Keeler in 1889, as “of a pale pink colour, slightly lighter in the middle. Its outline was a fairly true ellipse, framed in by bright white clouds.”[1083] The fading continuously in progress from 1887 was temporarily interrupted in 1891. The revival, indeed, was brief. Professor Barnard wrote in August, 1892: “The great red spot is still visible, but it has just passed through a crisis that seemingly threatened its very existence. For the past month it has been all but impossible to catch the feeblest trace of the spot, though the ever-persistent bay in the equatorial belt close north of it, and which has been so intimately connected with the history of the red spot, has been as conspicuous as ever. It is now, however, possible to detect traces of the entire spot. An obscuring medium seems to have been passing over it, and has now drifted somewhat preceding the spot.”[1084]

The object is now always inconspicuous, and often practically invisible, and may be said to float passively in the environing medium.[1085] Yet there are sparks beneath the ashes. A rosy tinge faintly suffused it in April, 1900,[1086] and its absolute end may still be remote.

The extreme complexity of the planet’s surface-movements has been strikingly evinced by Mr. Stanley Williams’s detailed investigations. He enumerated in 1896[1087] nine principal currents, all flowing parallel to the equator, but unsymmetrically placed north and south of it, and showing scant signs of conformity to the solar rule of retardation with increase of latitude. The linear rate of the planet’s equatorial rotation was spectroscopically determined by Bélopolsky and Deslandres in 1895. Both found it to fall short of the calculated speed, whence an enlargement, by self-refraction, of the apparent disc was inferred.[1088]

Jupiter was systematically photographed with the Lick 36-inch telescope during the oppositions of 1890, 1891, and 1892, the image thrown on the plates (after eightfold direct enlargement) being one inch in diameter. Mr. Stanley Williams’s measurements and discussion of the set for 1891 showed the high value of the materials thus collected, although much more minute details can be seen than can at present be photographed. The red spot shows as “very distinctly annular” in several of these pictures.[1089] Recently, the planet has been portrayed by Deslandres with the 62-foot Meudon refractor.[1090] The extreme actinic feebleness of the equatorial bands was strikingly apparent on his plates.

In 1870, Mr. Ranyard[1091]—whose death, December 14, 1894, was a serious loss to astronomy—acting upon an earlier suggestion of Sir William Huggins, collected records of unusual appearances on the disc of Jupiter, with a view to investigate the question of their recurrence at regular intervals. He concluded that the development of the deeper tinges of colour, and of the equatorial “port-hole” markings girdling the globe in regular alternations of bright and dusky, agreed, so far as could be ascertained, with epochs of sun-spot maximum. The further inquiries of Dr. Lohse at Bothkamp in 1873[1092] went to strengthen the coincidence, which had been anticipated *à priori* by Zöllner in 1871.[1093]

Moreover, separate and distinct evidence was alleged by Mr. Denning in 1899 of decennial outbreaks of disturbance in north temperate regions.[1094] It may, indeed, be taken for granted that what Hahn terms the universal pulse of the solar system[1095] affects the vicissitudes of Jupiter; but the law of those vicissitudes is far from being so obviously subordinate to the rhythmical flow of central disturbance as are certain terrestrial phenomena. The great planet, being in fact himself a "semi-sun," may be regarded as an originator, no less than a recipient, of agitating influences, the combined effects of which may well appear insubordinate to any obvious law.

It is likely that Saturn is in a still earlier stage of planetary development than Jupiter. He is the lightest for his size of all the planets. In fact, he would float in water. And since his density is shown, by the amount of his equatorial bulging, to increase centrally,[1096] it follows that his superficial materials must be of a specific gravity so low as to be inconsistent, on any probable supposition, with the solid or liquid states. Moreover, the chief arguments in favour of the high temperature of Jupiter, apply, with increased force, to Saturn; so that it may be concluded, without much risk of error, that a large proportion of his bulky globe, 73,000 miles in diameter, is composed of heated vapours, kept in active and agitated circulation by the process of cooling.

His unique set of appendages has, since the middle of the last century, formed the subject of searching and fruitful inquiries, both theoretical and telescopic. The mechanical problem of the stability of Saturn's rings was left by Laplace in a very unsatisfactory condition. Considering them as rotating solid bodies, he pointed out that they could not maintain their position unless their weight were in some way unsymmetrically distributed; but made no attempt to determine the kind or amount of irregularity needed to secure this end. Some observations by Herschel gave astronomers an excuse for taking for granted the fulfilment of the condition thus vaguely postulated; and the question remained in abeyance until once more brought prominently forward by the discovery of the dusky ring in 1850.

The younger Bond led the way, among modern observers, in denying the solidity of the structure. The fluctuations in its aspect were, he asserted in 1851,[1097] inconsistent with such a hypothesis. The fine dark lines of division, frequently detected in both bright rings, and as frequently relapsing into imperceptibility, were due, in his opinion, to the real nobility of their particles, and indicated a fluid formation. Professor Benjamin Peirce of Harvard University immediately followed with a demonstration, on abstract grounds, of their non-solidity.[1098] Streams of some fluid denser than water were, he maintained, the physical reality giving rise to the anomalous appearance first disclosed by Galileo's telescope.

The mechanism of Saturn's rings, proposed as the subject of the Adams Prize, was dealt with by James Clerk Maxwell in 1857. His investigation forms the groundwork of all that is at present known in the matter. Its upshot was to show that neither solid nor fluid rings could continue to exist, and that the only possible composition of the system was by an aggregated multitude of unconnected particles, each revolving independently in a period corresponding to its distance from the planet.[1099] This idea of a satellite-formation had been, remarkably enough, several times entertained and lost sight of. It was first put forward by Roberval in the seventeenth century, again by Jacques Cassini in 1715, and with perfect definiteness by Wright of Durham in 1750.[1100] Little heed, however, was taken of these casual anticipations of a truth which reappeared, a virtual novelty, as the legitimate outcome of the most refined modern methods.

The details of telescopic observation accord, on the whole, admirably with this hypothesis. The displacements or disappearance of secondary dividing-lines—the singular striated appearance, first remarked by Short in the eighteenth century, last by Perrotin and Lockyer at Nice, March 18, 1884[1101]—show the effects of waves of disturbance traversing a moving mass of gravitating particles;[1102] the broken and changing line of the planet's shadow on the ring gives evidence of variety in the planes of the orbits described by those particles. The whole ring-system, too, appears to be somewhat elliptical.[1103]

The satellite-theory has derived unlooked-for support from photometric inquiries. Professor Seeliger pointed out in 1888[1104] that the unvarying brilliancy of the outer rings under all angles of illumination, from 0° to 30°, can be explained from no other point of view. Nor does the constitution of the obscure inner ring offer any difficulty. For it is doubtless formed of similar small bodies to those aggregated in the lucid members of the system, only much more thinly strewn, and reflecting, consequently, much less light. It is not, indeed, at first easy to see why these sparser flights should show as a dense dark shading on the body of Saturn. Yet this is invariably the case. The objection has been urged by Professor Hastings of Baltimore. The brightest parts of these appendages, he remarked,[1105] are more lustrous than the globe they encircle; but if the inner ring consists of identical materials, possessing presumably an equal reflective capacity, the mere fact of their scanty distribution would not cause them to show as dark against the same globe. Professor Seeliger, however, replied[1106] that the darkening is due to the never-ending swarms of their separate shadows transiting the planet's disc. Sunlight is not, indeed, wholly excluded. Many rays come and go between the open ranks of the meteorites. For the dusky ring is transparent. The planet it encloses shows through it, as if veiled with a strip of crape. A beautiful illustration of its quality in this respect was derived by Professor Barnard from an eclipse of Japetus, November 1, 1889.[1107] The eighth moon remained steadily visible during its passage through the shadow of the inner ring, but with a progressive loss of lustre in approaching its bright neighbour. There was no breach of continuity. The satellite met no gap, corresponding to that between the dusky ring and the body of Saturn, through which it could shine with undiminished light, but was slowly lost sight of as it plunged into deeper and deeper gloom. The important facts were thus established, that the brilliant and obscure rings merge into each other, and that the latter thins out towards the Saturnian globe.

The meteoric constitution of these appendages was beautifully demonstrated in 1895 by Professor Keeler,[1108] then director of the Alleghany Observatory, Pittsburgh. From spectrographs taken with the slit adjusted to coincidence with the equatorial plane of the system, he determined the comparative radial velocities of its different parts. And these supply a crucial test of Clerk Maxwell's theory. For if the rings were solid, the swiftest rates of rotation should be at their outer edges, corresponding to wider circles described in the same period; while, if they are pulverulent, the inverse relation must hold good. This proved to be actually the case. The motion slowed off outward, in agreement with the diminishing speed of particles travelling freely, each in its own orbit. Keeler's result was promptly confirmed by Campbell,[1109] as well as by Deslandres and Bélopolsky.

A question of singular interest, and one which we cannot refrain from putting to ourselves, is—whether we see in the rings of Saturn a finished structure, destined to play a permanent part in the economy of the system; or whether they represent merely a stage in the process of development out of the chaotic state in which it is impossible to doubt that the materials of all planets were originally merged. M. Otto Struve attempted to give a definite answer to this important query.

A study of early and later records of observations disclosed to him, in 1851, an apparent progressive approach of the inner edge of the bright ring to the planet. The rate of approach he estimated at about fifty-seven English miles a year, or 11,000 miles during the 194 years elapsed since the time of Huygens.[1110] Were it to continue, a collapse of the system must be far advanced within three centuries. But was the change real or illusory—a plausible, but deceptive inference from insecure data? M. Struve resolved to put it to the test. A set of elaborately careful micrometrical measures of the dimensions of Saturn's rings, executed by himself at Pulkowa in the autumn of 1851, was provided as a standard of future comparison; and he was enabled to renew them, under closely similar circumstances, in 1882.[1111] But the expected diminution of the space between Saturn's globe and his rings had not taken place. A slight extension in the width of the system, both outward and inward, was indeed, hinted at; and it is worth notice that just such a separation of the rings was indicated by Clerk Maxwell's theory, so that there is an *à priori* likelihood of its being in progress. Yet Hall's measures in 1884-87[1112] failed to supply evidence of alteration with time; and Barnard's, executed at Lick in 1894-95,[1113] showed no sensible divergence from them. Hence, much weight cannot be laid upon Huygens's drawings and descriptions, which had been held to prove conclusively a partial filling up, since 1657, of the interval between the ring and the planet.[1114]

The rings of Saturn replace, in Professor G. H. Darwin's view,[1115] an abortive satellite, scattered by tidal action into annular form. For they lie closer to the planet than is consistent with the integrity of a revolving body of reasonable bulk. The limit of possible existence for such a mass was fixed by Roche of Montpellier, in 1848,[1116] at 2·44 mean radii of its primary; while the outer edge of the ring-system is distant 2·38 radii of Saturn from his centre. The virtual discovery of its pulverulent condition dates, then, according to Professor Darwin, from 1848. He conjectures that the appendage will eventually disappear, partly through the dispersal of its constituent particles inward, and their subsidence upon the planet's surface, partly by their dispersal outward, to a region beyond "Roche's limit," where coalescence might proceed unhindered by the strain of unequal attractions. One modest satellite, revolving inside Mimas, would then be all that was left of the singular appurtenances we now contemplate with admiration.

There seems reason to admit that Kirkwood's law of commensurability has had some effect in bringing about the present distribution of the matter composing them. Here the influential bodies are Saturn's moons, while the divisions and boundaries of the rings represent the spaces where their disturbing action conspires to eliminate revolving particles. Kirkwood, in fact, showed, in 1867,[1117] that a body circulating in the chasm between the bright rings known as "Cassini's division," would have a period nearly commensurable with those of *four* out of the eight moons; and Meyer of Geneva subsequently calculated all such combinations, with the result of bringing out coincidences between regions of maximum perturbation and the limiting and dividing lines of the system.[1118] This is in itself a strong confirmation of the view that the rings are made up of independently revolving small bodies.

On December 7, 1876, Professor Asaph Hall discovered at Washington a bright equatorial spot on Saturn, which he followed and measured through above sixty rotations, each performed in ten hours fourteen minutes twenty-four seconds.[1119] This, he was careful to add, represented the period, not necessarily of the *planet*, but only of the individual spot. The only previous determination of Saturn's axial movement (setting aside some insecure estimates by Schröter) was Herschel's in 1794, giving a period of ten hours sixteen minutes. The substantial accuracy of Hall's result was verified by Mr. Denning in 1891.[1120] In May and June of that year, ten vague bright markings near the equator were watched by Mr. Stanley Williams, who derived from them a rotation period only two seconds shorter than that determined at Washington. Nevertheless, similarly placed spots gave in 1892 and 1893 notably quicker rates;[1121] so that the task of timing the general drift of the Saturnian surface by the displacements of such objects is hampered, to an indefinite extent, by their individual proper motions.

Saturn's outermost satellite, Japetus, is markedly variable—so variable that it sends us, when brightest, just 4-1/2 times as much light as when faintest. Moreover, its fluctuations depend upon its orbital position in such a way as to make it a conspicuous telescopic object when west, a scarcely discernible one when east of the planet. Herschel's inference[1122] of a partially obscured globe turning always the same face towards its primary seems the only admissible one, and is confirmed by Pickering's measurements of the varying intensity of its light. He remarked further that the dusky and brilliant hemispheres must be so posited as to divide the disc, viewed from Saturn, into nearly equal parts; so that this Saturnian moon, even when "full," appears very imperfectly illuminated over one-half of its surface.[1123]

Zöllner estimated the albedo of Saturn at 0·51, Müller at 0·88, a value impossibly high, considering that the spectrum includes no vestige of original emissions. Closely similar to that of Jupiter, it shows the distinctive dark line in the red (wave-length 618), which we may call the "red-star line"; and Janssen, from the summit of Etna in 1867[1124] found traces in it of aqueous absorption. The light from the ring appears to be pure reflected sunshine unmodified by original atmospheric action.[1125]

Uranus, when favourably situated, can easily be seen with the naked eye as a star between the fifth and sixth magnitudes. There is indeed, some reason to suppose that he had been detected as a wandering orb by savage "watchers of the skies" in the Pacific long before he swam into Herschel's ken. Nevertheless, inquiries into his physical habitudes are still in an early stage. They are exceedingly difficult of execution, even with the best and largest modern telescopes; and their results remain clouded with uncertainty.

It will be remembered that Uranus presents the unusual spectacle of a system of satellites travelling nearly at right angles to the plane of the ecliptic. The existence of this anomaly gives a special interest to investigations of his axial movement, which might be presumed, from the analogy of the other planets, to be executed in the same tilted plane. Yet this is far from being certainly the case.

Mr. Buffham in 1870-72 caught traces of bright markings on the Uranian disc, doubtfully suggesting a rotation in about twelve hours in a plane *not* coincident with that in which his satellites circulate.[1126] Dusky bands resembling those of Jupiter, but very faint, were barely perceptible to Professor Young at Princeton in 1883. Yet, though almost necessarily inferred to be equatorial, they made a considerable angle with the trend of the satellites' orbits.[1127] More distinctly by the brothers Henry, with the aid of their fine refractor, two gray parallel rulings, separated by a brilliant zone, were discerned every clear night at Paris from January to June, 1884.[1128] What were taken to be the polar regions appeared comparatively dusky. The direction of the equatorial rulings (for so we may safely call them) made an angle of 40° with the satellites' line of travel. Similar observations were made at Nice by MM. Perrotin and Thollon, March to June, 1884, a lucid spot near the equator, in addition, indicating rotation in a period of about ten hours.[1129] The discrepancy was, however, considerably reduced by Perrotin's study of the planet in 1889 with the new 30-inch equatoreal.[1130] The dark bands, thus viewed to better advantage than in 1884, appeared to deviate no more than 10° from the satellites' orbit-plane. No definitive results, on the other hand, were derived by Professors Holden, Schaeberle, and Keeler from their observations of Uranus in 1889-90 with the potent instrument on Mount Hamilton. Shadings, it is true, were almost always, though faintly, seen; but they appeared under an anomalous, possibly an illusory aspect. They consisted, not of parallel, but of forked bands.[1131]

Measurements of the little sea-green disc which represents to us the massive bulk of Uranus, by Young, Schiaparelli,[1132] Safarik, H. C. Wilson[1133] and Perrotin, prove it to be quite distinctly *bulged*. The compression at once caught Barnard's trained eye in 1894,[1134] when he undertook at Lick a micrometrical investigation of the system; and he was surprised to perceive that the major axis of the elliptical surface made an angle of about 28° with the line of travel pursued by the satellites. Nothing more can be learned on this curious subject for some years, since the pole of the planet is just now turned nearly towards the earth; but Barnard's conclusion is unlikely to be seriously modified. He fixed the mean diameter of Uranus at 34,900 miles. But this estimate was materially reduced through Dr. See's elimination of irradiative effects by means of daylight measures, executed at Washington in 1901.[1135]

The visual spectrum of this planet was first examined by Father Secchi in 1869, and later, with more advantages for accuracy, by Huggins, Vogel,[1136] and Keeler.[1137] It is a very remarkable one. In lieu of the reflected Fraunhofer lines, imperceptible perhaps through feebleness of light, six broad bands of original absorption appear, one corresponding to the blue-green ray of hydrogen (F), another to the "red-star line" of Jupiter and Saturn, the rest as yet unidentified. The hydrogen band seems much too strong and diffuse to be the mere echo of a solar line, and might accordingly be held to imply the presence of free hydrogen in the Uranian atmosphere. This, however, would be difficult of reconcilement with Keeler's identification of an absorption-group in the yellow with a telluric waterband.

Notwithstanding its high albedo—0·62, according to Zöllner—proof is wanting that any of the light of Uranus is inherent. Mr. Albert Taylor announced, indeed, in 1889, his detection, with Common's giant reflector, of bright flutings in its spectrum;[1138] but Professor Keeler's examination proved them to be merely contrast effects.[1139] Sir William and Lady Huggins, moreover, obtained about the same time a photograph purely solar in character. The spectrum it represented was crossed by numerous Fraunhofer lines, and by no others. It was, then, presumably composed entirely of reflected light.

Judging from the indications of an almost evanescent spectrum, Neptune, as regards physical condition, is the twin of Uranus, as Saturn of Jupiter. Of the circumstances of his rotation we are as good as completely ignorant. Mr. Maxwell Hall, indeed, noticed at Jamaica, in November and December, 1883, certain rhythmical fluctuations of brightness, suggesting revolution on an axis in slightly less than eight hours;[1140] but Professor Pickering reduces the supposed variability to an amount altogether too small for certain perception, and Dr. G. Müller denies its existence *in toto*. It is true their observations were not precisely contemporaneous with those of Mr. Hall[1141] who believes the partial obscurations recorded by himself to have been of a passing kind, and to have suddenly ceased after a fortnight of prevalence. Their less conspicuous renewal was visible to him in November, 1884, confirming a rotation period of 7·92 hours.

It was ascertained at first by indirect means that the orbit of Neptune's satellite is inclined about 20° to his equator. Mr. Marth[1142] having drawn attention to the rapid shifting of its plane of motion, M. Tisserand and Professor Newcomb[1143] independently published the conclusion that such shifting necessarily results from Neptune's ellipsoidal shape. The movement is of the kind exemplified—although with inverted relations—in the precession of the equinoxes. The pole of the satellite, owing to the pull of Neptune's equatorial protuberance, describes a circle round the pole of his equator in a retrograde direction, and in a period of over five hundred years. The amount of compression indicated for the primary body is, at the outside, 1/85; whence it can be inferred that Neptune possesses a lower rotatory velocity than the other giant planets. Direct verification of the trend theoretically inferred for the satellite's movement was obtained by Dr. See in 1899. The Washington 26-inch refractor disclosed to him, under exceptionally favourable conditions, a set of equatorial belts on the disc of Neptune, and they took just the direction prescribed by theory. Their objective reality cannot be doubted, although Barnard was unable, either with the Lick or the Yerkes telescope,[1144] to detect any definite markings on this planet. Its diameter was found by him to be 32,900 miles.

The possibility that Neptune may not be the most remote body circling round the sun has been contemplated ever since he has been known to exist. Within the last few years the position at a given epoch of a planet far beyond his orbital verge has been approximately fixed by two separate investigators.

Professor George Forbes of Edinburgh adopted in 1880 a novel plan of search for unknown members of the solar system, the first idea of which was thrown out by M. Flammarion in November, 1879.[1145] It depends upon the movements of comets. It is well known that those of moderately short periods are, for a reason already explained, connected with the larger planets in such a way that the cometary aphelia fall near some planetary orbit. Jupiter claims a large retinue of such partial dependents, Neptune owns six, and there are two considerable groups, the farthest distances of which from the sun lie respectively near 100 and 300 times that of the earth. At each of these vast intervals, one involving a period of 1,000, the other of 5,000 years, Professor Forbes maintains that an unseen planet circulates. He even computed elements for the nearer of the two, and fixed its place on the celestial sphere;[1146] but the photographic searches made for it by Dr. Roberts at Crowborough and by Mr. Wilson at Daramona proved unavailing. Undeterred by Deichmüller's discouraging opinion that cometary orbits extending beyond the recognised bounds of the solar system are too imperfectly known to serve as the basis of trustworthy conclusions,[1147] the Edinburgh Professor returned to the attack in 1901.[1148] He now sought to prove that the lost comet of 1556 actually returned in 1844, but with elements so transformed by ultra-Neptunian perturbations as to have escaped immediate identification. If so, the "wanted" planet has just entered the sign Libra, and, being larger than Jupiter, should be possible to find.

Almost simultaneously with Forbes, Professor Todd set about groping for the same object by the help of a totally different set of indications. Adams's approved method commended itself to him; but the hypothetical divagations of Neptune having scarcely yet had time to develop, he was thrown back upon the "residual errors" of Uranus. They gave him a virtually identical situation for the new planet with that derived from the clustering of cometary aphelia.[1149] Yet its assigned distance was little more than half that of the nearer of Professor Forbes's remote pair, and it completed a revolution in 375 instead of 1,000 years. The agreement in them between the positions determined, on separate grounds, for the ultra-Neptunian traveller was merely an odd coincidence; nor can we be certain, until it is seen, that we have really got into touch with it.

FOOTNOTES:

[965] *Phil. Trans.*, vol. lxxiv., p. 260.

[966] *Novæ Observationes*, p. 105.

[967] *Phil. Trans.*, vol. i., p. 243.

[968] *Mém. de l'Ac.*, 1720, p. 146.

[969] *Phil. Trans.*, vol. lxxiv., p. 273.

[970] A large work, entitled *Areographische Fragmente*, in which Schröter embodied the results of his labours on Mars, 1785-1803, narrowly escaped the conflagration of 1813, and was published at Leyden in 1881.

[971] *Beiträge*, p. 124.

[972] *Mem. R. A. Soc.*, vol. xxxii., p. 183.

[973] *Astr. Nach.*, No. 1,468.

[974] *Observatory*, vol. viii., p. 437.

[975] *Month. Not.*, vols. xxviii., p. 37; xxix., p. 232; xxxiii., p. 552.

[976] Flammarion, *L'Astronomie*, t. i., p. 266.

[977] Smyth, *Cel. Cycle*, vol. i., p. 148 (1st ed.).

[978] *Phil. Trans.*, vol. cxxi., p. 417.

[979] *Month. Not.*, vol. xxv., p. 227.

[980] *Phil. Mag.*, vol. xxxiv., p. 75.

[981] Proctor, *Quart. Jour. of Science*, vol. x., p. 185; Maunder, *Sunday Mag.*, January, February, March, 1882; Campbell, *Publ. Astr. Pac. Soc.*, vol. vi., p. 273.

[982] *Am. Jour. of Sc.*, vol. xxviii., p. 163.

[983] Burton, *Trans. Roy. Dublin Soc.*, vol. i., 1880, p. 169.

[984] *Month. Not.*, vol. xxvii., p. 179; *Astroph. Journ.*, vol. i., p. 193.

[985] *Untersuchungen über die Spectra der Planeten*, p. 20; *Astroph. Journ.*, vol. i., p. 203.

[986] *Publ. Astr. Pac. Soc.*, vols. vi., p. 228; ix., p. 109; *Astr. and Astroph.*, vol. xiii., p. 752; *Astroph. Jour.*, vol. ii., p. 28.

[987] *Ibid.*, vol. v., p. 328.

[988] *Ibid.*, vols. i., p. 311; iii., p. 254.

[989] C. Christiansen, *Beiblätter*, 1886, p. 532.

[990] *Astr. and Astrophysics*, vol. xi., p. 671.

[991] Flammarion, *La Planète Mars*, p. 574.

[992] *Mémoires Couronnés*, t. xxxix.

[993] Lockyer, *Nature*, vol. xlvi., p. 447.

[994] *Mem. Spettr. Italiani*, t. xi., p. 28.

[995] *Bull. Astr.*, t. iii., p. 324.

[996] *Journ. Brit. Astr. Ass.*, vol. i., p. 88.

[997] *Publ. Pac. Astr. Soc.*, vol. ii., p. 299; Percival Lowell, *Mars*, 1896; *Annals of the Lowell Observatory*, vol. ii., 1900.

[998] *Old and New Astr.*, p. 545.

[999] *L'Astronomie*, t. xi., p. 445.

[1000] *La Planète Mars*, p. 588.

[1001] *Month. Notices*, vol. lvi., p. 166.

[1002] *L'Astronomie*, t. viii.

[1003] *Astr. Nach.*, No. 3,271; *Astr. and Astrophysics*, vol. xiii., p. 716.

[1004] *Month. Not.*, vol. xxxviii., p. 41; *Mem. Roy. Astr. Soc.*, vol. xliv., p. 123.

[1005] *Astr. and Astrophysics*, vol. xi., p. 668.

[1006] *Ibid.*, p. 850.

[1007] *Comptes Rendus*, t. cxv., p. 379.

[1008] *Astr. Jour.*, No. 384; *Publ. Astr. Pac. Soc.*, vol. vi., p. 109. *Cf. Observatory* vol. xvii., pp. 295-336.

[1009] See Mr. Wentworth Erck's remarks in *Trans. Roy. Dublin Soc.*, vol. i., p. 29.

[1010] *Month. Not.*, vol. xxxviii., p. 206.

[1011] *Annals Harvard Coll. Obs.*, vol. xi., pt. ii., p. 217.

[1012] Young, *Gen. Astr.*, p. 366.

[1013] Campbell, *Publ. Pac. Astr. Soc.*, vol. vi., p. 270.

[1014] *Astr. Nach.*, No. 3,319.

[1015] *Witch of Atlas*, stanza iii. I am indebted to Dr. Garnett for the reference.

[1016] Recommended by Chandler, *Astr. Jour.*, No. 452.

[1017] *Harvard Circulars*, Nos. 36, 37, 51.

[1018] *Astr. Nach.*, No. 3,687.

[1019] Montangerand, *Comptes Rendus*, March 11, 1901.

[1020] Pickering, *Astroph. Jour.*, vol. xiii., p. 277.

[1021] *Harvard Circular*, No. 58.

[1022] *Astr. Nach.*, No. 752.

[1023] L. Niesten, *Annuaire*, Bruxelles, 1881, p. 269.

[1024] According to Svedstrup (*Astr. Nach.*, Nos. 2,240-41), the inclination to the ecliptic of the "mean asteroid's" orbit is = 6°.

[1025] *Smiths.* Report, 1876, p. 358; *The Asteroids* (Kirkwood), p. 42, 1888.

[1026] Tisserand, *Annuaire*, Paris, 1891, p. B. 15; Newcomb, *Astr. Jour.*, No. 477; Backlund, *Bull. Astr.*, t. xvii., p. 81; Parmentier, *Bull. Soc. Astr. de France*, March, 1896; Observatory, vol. xviii., p. 207.

[1027] Berberich, *Astr. Nach.*, No. 3,088.

[1028] *Bull. Astr.*, t. xviii., p. 39.

[1029] *The Asteroids*, p. 48; *Publ. Astr. Pac. Soc.*, vols. ii., p. 48; iii., p. 95.

[1030] *Comptes Rendus*, t. xxxvii., p. 797.

[1031] *Bull. Astr.*, t. v., p. 180.

[1032] *Annuaire*, Bruxelles, 1881, p. 243.

[1033] *Johns Hopkins Un. Circular*, January, 1895; *Observatory*, vol. xviii., p. 127.

[1034] *Harvard Annals*, vol. xi., part ii., p. 294.

[1035] *Astr. Nach.*, Nos. 2,724-5.

[1036] *Month. Not.*, vol. lxi., p. 69.

[1037] *Astroph. Jour.*, vol. vii., p. 25.

[1038] *Spectra der Planeten*, p. 24.

[1039] Tome i., p. 93.

[1040] *Berlinische Monatsschrift*, 1785, p. 211.

[1041] *Month. Not.*, vol. xiii., p. 40.

[1042] *Mem. Am. Ac.*, vol. viii., p. 221.

[1043] *Photom. Unters.*, p. 303.

[1044] *Astr. Nach.*, No. 1,851.

[1045] *Mém. de l'Ac.*, t. x., p. 514.

[1046] *Ibid.*, 1692, p. 7.

[1047] *Month. Not.*, vol. xliv., p. 63.

[1048] *Photom. Unters.*, pp. 165, 273; *Potsdam Publ.*, No. 30.

[1049] Vogel, *Sp. der Planeten*, p. 33, *note*.

[1050] *Proc. Roy. Soc.*, vol. xviii., p. 250.

[1051] *Month. Not.*, vol. xl., p. 433.

[1052] *Sitzungsberichte*, Berlin, 1895, ii., p. 15.

[1053] The anomalous shadow-effects recorded by Webb (*Cel. Objects*, p. 170, 4th ed.) are obviously of atmospheric and optical origin.

[1054] Engelmann, *Ueber die Helligkeitsverhältnisse der Jupiterstrabanten*, p. 59.

[1055] *Month. Not.*, vol. xxviii., p. 11.

[1056] *Observatory*, vol. vii., p. 175.

[1057] *Month. Not.*, vol. xlviii., p. 43.

[1058] *Publ. Astr. Pac. Soc.*, vol. ii., p. 296.

[1059] Pickering failed to obtain any photometric evidence of their variability. *Harvard Annals*, vol. xi., p. 245.

[1060] *Astr. and Astroph.*, vol. xii., pp. 194, 481.

[1061] *Annals Lowell Obs.*, vol. ii., pt. i.

[1062] *Astr. Nach.*, Nos. 2,995, 3,206; *Month. Not.*, vols. li., p. 556; liv., p. 134. Barnard remains convinced that the oval forms attributed to Jupiter's satellites are illusory effects of their markings. *Astr. Nach.*, Nos. 3,206, 3,453; *Astr. and Astroph.*, vol. xiii., p. 272.

[1063] *Publ. Astr. Pac. Soc.*, vol. iii., p. 355.

[1064] *Astr. Nach.*, No. 1,017.

[1065] *Publ. Astr. Pac. Soc.*, vol. iii., p. 359.

[1066] *Astr. Nach.*, No. 3,432.

[1067] *Astr. Jour.*, Nos. 275, 325, 367, 472; *Observatory*, vol. xv., p. 425.

[1068] Tisserand, *Comptes Rendus*, October 8, 1894; Cohn, *Astr. Nach.*, No. 3,404.

[1069] *Bull. Ac. R. Bruxelles*, t. xlviii., p. 607.

[1070] *Astr. Nach.*, No. 2,294.

[1071] *Ibid.*, No. 2,284.

[1072] Denning, *Month. Not.*, vol. xliv., pp. 64, 66; *Nature*, vol. xxv., p. 226.

[1073] *Sidereal Mess.*, December, 1886, p. 289.

[1074] *Astr. Nach.*, Nos. 2,280, 2,282.

[1075] *Month. Not.*, vol. xlvi., p. 117.

[1076] *Proc. Roy. Soc. N. S. Wales*, vol. xiv., p. 68.

[1077] *Phil. Trans.*, vol. i., p. 143.

[1078] For indications relative to the early history of the red spot, see Holden, *Publ. Astr. Pac. Soc.*, vol. ii., p. 77; Noble, *Month. Not.*, vol. xlvii., p. 515; A. S. Williams, *Observatory*, vol. xiii., p. 338.

[1079] *Astr. and Astrophysics*, vol. xi., p. 192.

[1080] *Month. Not.*, vol. l., p. 520.

[1081] *Observatory*, vol. xiii., pp. 297, 326.

[1082] *Trans. R. Dublin Soc.*, vol. iv., p. 271, 1889.

[1083] *Publ. Astr. Pac. Soc.*, vol. ii., p. 289.

[1084] *Astr. and Astrophysics*, vol. xi., p. 686.

[1085] Denning, *Knowledge*, vol. xxiii., p. 200; *Observatory*, vol. xxiv., p. 312; *Pop. Astr.*, vol. ix., p. 448; *Nature*, vol. lv., p. 89.

[1086] Williams, *Observatory*, vol. xxiii., p. 282.

[1087] *Month. Not.*, vol. lvi., p. 143.

[1088] Bélopolsky, *Astr. Nach.*, No. 3,326.

[1089] *Publ. Astr. Pac. Soc.*, vol. iv., p. 176.

[1090] *Bull. Astr.*, 1900, p. 70.

[1091] *Month. Not.*, vol. xxxi., p. 34.

[1092] *Beobachtungen*, Heft ii., p. 99.

[1093] *Ber. Sächs. Ges. der Wiss.*, 1871, p. 553.

[1094] *Month. Not.*, vol. lix., p. 76.

[1095] *Beziehungen der Sonnenfleckenperiode*, p. 175.

[1096] A. Hall, *Astr. Nach.*, No. 2,269.

[1097] *Astr. Jour.* (Gould's), vol. ii., p. 17.

[1098] *Ibid.*, p. 5.

[1099] *On the Stability of the Motion of Saturn's Rings*, p. 67.

[1100] *Mém. de l'Ac.*, 1715, p. 47; Montucla, *Hist. des Math.*, t. iv., p. 19; *An Original Theory of the Universe*, p. 115.

[1101] *Comptes Rendus*, t. xcviii., p. 718.

[1102] Proctor, *Saturn and its System* (1865), p. 125.

[1103] Perrotin, *Comptes Rendus*, t. cvi., p. 1716.

[1104] *Abhandl. Akad. der Wiss.*, Munich, Bd. xvi., p. 407.

[1105] *Smiths. Report*, 1880 (Holden).

[1106] Quoted by Dr. E. Anding, *Astr. Nach.*, No. 2,881.

[1107] *Astr. and Astrophysics*, vol. xi., p. 119; *Month. Not.*, vol. l., p. 108.

[1108] *Astroph. Jour.*, vol. i., p. 416.

[1109] *Ibid.*, vol. ii., p. 127.

[1110] *Mém. de l'Ac. Imp.* (St. Petersb.), t. vii., 1853, p. 464.

[1111] *Astr. Nach.*, No. 2,498.

[1112] *Washington Observations*, App. ii., p. 22

[1113] *Month. Not.*, vol. lvi., p. 163.

[1114] T. Lewis, *Observatory*, vol. xviii., p. 379.

[1115] *Harper's Magazine*, June, 1889.

[1116] *Mém. de l'Acad. de Montpellier*, t. viii., p. 296, 1873.

[1117] *Meteoric Astronomy*, chap. xii. He carried the subject somewhat farther in 1871. See *Observatory*, vol. vi., p. 335.

[1118] *Astr. Nach.*, No. 2,527.

[1119] *Amer. Jour. of Sc.*, vol. xiv., p. 325.

[1120] *Observatory*, vol. xiv., p. 369.

[1121] *Month. Not.*, vol. liv., p. 297.

[1122] *Phil. Trans.*, vol. lxxxii., p. 14.

[1123] *Smiths. Report*, 1880.

[1124] *Comptes Rendus*, t. lxiv., p. 1304.

[1125] Huggins, *Proc. R. Soc.*, vol. xlvi., p. 231; Keeler, *Astr. Nach.*, No. 2,927; Vogel, *Astroph. Jour.*, vol. i., p. 278.

[1126] *Month. Not.*, vol. xxxiii., p. 164.

[1127] *Astr. Nach.*, No 2,545.

[1128] *Comptes Rendus*, t. xcviii., p. 1419.

[1129] *Comptes Rendus*, t. xcviii., pp. 718, 967.

[1130] *V. J. S. Astr. Ges.*, Jahrg. xxiv., p. 267.

[1131] *Publ. Astr. Pac. Soc.*, vol. iii., p. 287.

[1132] *Astr. Nach.*, No. 2,526.

[1133] *Ibid.*, No. 2,730.

[1134] *Astr. Jour.*, Nos. 370, 374.

[1135] *Astr. Nach.*, No. 3,768.

[1136] *Ann. der Phys.*, Bd. clviii., p. 470; *Astroph. Jour.*, vol. i., p. 280.

[1137] *Astr. Nach.*, No. 2,927.

[1138] *Month. Not.*, vol. xlix., p. 405.

[1139] Astr. Nach., No. 2,927; Scheiner’s *Spectralanalyse*, p. 221.

[1140] *Month. Not.*, vol. xliv., p. 257.

[1141] *Observatory*, vol. vii., pp. 134, 221, 264.

[1142] *Month. Not.*, vol. xlvi., p. 507.

[1143] *Comptes Rendus*, t. cvii., p. 804; *Astr. and Astroph.*, vol. xiii., p. 291; *Astr. Jour.*, No. 186.

[1144] *Astr. Jour.*, Nos. 342, 436, 508.

[1145] *Astr. Pop.*, p. 661; *La Nature*, January 3, 1880.

[1146] *Proc. Roy. Soc. Edinb.*, vols. x., p. 429; xi., p. 89.

[1147] *Vierteljahrsschrift. Astr. Ges.*, Jahrg. xxi., p. 206.

[1148] *Proc. Roy. Soc. Edinb.*, vol. xxiii., p. 370; *Nature*, vol. lxiv., p. 524.

[1149] *Amer. Jour. of Science*, vol. xx., p. 225.

CHAPTER IX

THEORIES OF PLANETARY EVOLUTION

We cannot doubt that the solar system, as we see it, is the result of some process of growth —that, during innumerable ages, the forces of Nature were at work upon its materials, blindly modelling them into the shape appointed for them from the beginning by Omnipotent Wisdom. To set ourselves to inquire what that process was may be an audacity, but it is a legitimate, nay, an inevitable one. For man's implanted instinct to "look before and after" does not apply to his own little life alone, but regards the whole history of creation, from the highest to the lowest—from the microscopic germ of an alga or a fungus to the visible frame and furniture of the heavens.

Kant considered that the inquiry into the mode of origin of the world was one of the easiest problems set by Nature; but it cannot be said that his own solution of it was satisfactory. He, however, struck out in 1755 a track which thought still pursues. In his *Allgemeine Naturgeschichte* the growth of sun and planets was traced from the cradle of a vast and formless mass of evenly diffused particles, and the uniformity of their movements was sought to be accounted for by the unvarying action of attractive and repulsive forces, under the dominion of which their development was carried forward.

In its modern form, the "Nebular Hypothesis" made its appearance in 1796.[1150] It was presented by Laplace with diffidence, as a speculation unfortified by numerical buttresses of any kind, yet with visible exultation at having, as he thought, penetrated the birth-secret of our system. He demanded, indeed, more in the way of postulates than Kant had done. He started with a sun ready made,[1151] and surrounded with a vast glowing atmosphere, extending into space out beyond the orbit of the farthest planet, and endowed with a slow rotatory motion. As this atmosphere or nebula cooled, it contracted; and as it contracted, its rotation, by a well-known mechanical law, became accelerated. At last a point arrived when tangential velocity at the equator increased beyond the power of gravity to control, and equilibrium was restored by the separation of a nebulous ring revolving in the same period as the generating mass. After a time, the ring broke up into fragments, all eventually reunited in a single revolving and rotating body. This was the first and farthest planet.

Meanwhile the parent nebula continued to shrink and whirl quicker and quicker, passing, as it did so, through successive crises of instability, each resulting in, and terminated by, the formation of a planet, at a smaller distance from the centre, and with a shorter period of revolution than its predecessor. In these secondary bodies the same process was repeated on a reduced scale, the birth of satellites ensuing upon their contraction, or not, according to circumstances. Saturn's ring, it was added, afforded a striking confirmation of the theory of annular separation,[1152] and appeared to have survived in its original form in order to throw light on the genesis of the whole solar system; while the four first discovered asteroids offered an example in which the *débris* of a shattered ring had failed to coalesce into a single globe.

This scene of cosmical evolution was a characteristic bequest from the eighteenth century to the nineteenth. It possessed the self-sufficing symmetry and entireness appropriate to the ideas of a time of renovation, when the complexity of nature was little accounted of in comparison with the imperious orderliness of the thoughts of man. Since its promulgation, however, knowledge has transgressed many boundaries, and set at naught much ingenious theorising. How has it fared with Laplace's sketch of the origin of the world? It has at least not been discarded as effete. The groundwork of speculation on the subject is still furnished by it. It is, nevertheless, admittedly inadequate. Of much that exists it gives no account, or an erroneous one. The march of events certainly did not everywhere—even if it did anywhere—follow the exact path prescribed for it. Yet modern science attempts to supplement, but scarcely ventures to supersede it.

Thought has, in many directions, been profoundly modified by Mayer's and Joule's discovery, in 1842, of the equivalence between heat and motion. Its corollary was the grand idea of the "conservation of energy," now one of the cardinal principles of science. This means that, under the ordinary circumstances of observation, the old maxim *ex nihilo nihil fit* applies to force as well as to matter. The supplies of heat, light, electricity, must be kept up, or the stream will cease to flow. The question of the maintenance of the sun's heat was thus inevitably raised; and with the question of maintenance that of origin is indissolubly connected.

Dr. Julius Robert Mayer, a physician residing at Heilbronn, was the first to apply the new light to the investigation of what Sir John Herschel had termed the "great secret." He showed that if the sun were a body either simply cooling or in a state of combustion, it must long since have "gone out." Had an equal mass of coal been set alight four or five centuries after the building of the Pyramid of Cheops, and kept burning at such a rate as to supply solar light and heat during the interim, only a few cinders would now remain in lieu of our undiminished glorious orb. Mayer looked round for an alternative. He found it in the "meteoric hypothesis" of solar conservation.[1153] The importance in the economy of our system of the bodies known as falling stars was then (in 1848) beginning to be recognised. It was known that they revolved in countless swarms round the sun; that the earth daily encountered millions of them; and it was surmised that the cone of the zodiacal light represented their visible condensation towards the attractive centre. From the zodiacal light, then, Mayer derived the store needed for supporting the sun's radiations. He proved that, by the stoppage of their motion through falling into the sun, bodies would evolve from 4,600 to 9,200 times as much heat (according to their ultimate velocity) as would result from the burning of equal masses of coal, their precipitation upon the sun's surface being brought about by the resisting medium observed to affect the revolutions of Encke's comet. There was, however, a difficulty. The quantity of matter needed to keep, by the sacrifice of its movement, the hearth of our system warm and bright would be very considerable. Mayer's lowest estimate put it at 94,000 billion kilogrammes per second, or a mass equal to that of our moon bi-annually. But so large an addition to the gravitating power of the sun would quickly become sensible in the movement of the bodies dependent upon him. Their revolutions would be notably accelerated. Mayer admitted that each year would be shorter than the previous one by a not insignificant fraction of a second, and postulated an unceasing waste of substance, such as Newton had supposed must accompany emission of the material corpuscles of light, to neutralise continual reinforcement.

Mayer's views obtained a very small share of publicity, and owned Mr. Waterston as their independent author in this country. The meteoric, or "dynamical," theory of solar sustentation was expounded by him before the British Association in 1853. It was developed with his usual ability by Lord Kelvin, in the following year. The inflow of meteorites, he remarked, "is the only one of all conceivable causes of solar heat which we know to exist from independent evidence."[1154] We know it to exist, but we now also know it to be entirely insufficient. The supplies presumed to be contained in the zodiacal light would be quickly exhausted; a constant inflow from space would be needed to meet the demand. But if moving bodies were drawn into the sun at anything like the required rate, the air, even out here at ninety-three millions of miles distance, would be thick with them; the earth would be red-hot from their impacts;[1155] geological deposits would be largely meteoric;[1156] to say nothing of the effects on the mechanism of the heavens. Lord Kelvin himself urged the inadmissibility of the "extra-planetary" theory of meteoric supply on the very tangible ground that, if it were true, the year would be shorter now, actually by six weeks, than at the opening of the Christian era. The "intra-planetary" supply, however, is too scanty to be anything more than a temporary makeshift.

The meteoric hypothesis was naturally extended from the maintenance of the sun's heat to the formation of the bodies circling round him. The earth—no less doubtless than the other planets—is still growing. Cosmical matter in the shape of falling stars and aërolites, to the amount, adopting Professor Newton's estimate, of 100 tons daily, is swept up by it as it pursues its orbital round. Inevitably the idea suggested itself that this process of appropriation gives the key to the life-history of our globe, and that the momentary streak of fire in the summer sky represents a feeble survival of the glowing hailstorm by which in old times it was fashioned and warmed. Mr. E. W. Brayley supported this view of planetary production in 1864,[1157] and it has recommended itself to Haidinger, Helmholtz, Proctor, and Faye. But the negative evidence of geological deposits appears fatal to it.

The theory of solar energy now generally regarded as the true one was enounced by Helmholtz in a popular lecture in 1854. It depends upon the same principle of the equivalence of heat and motion which had suggested the meteoric hypothesis. But here the movement surrendered and transformed belongs to the particles, not of any foreign bodies, but of the sun itself. Drawn together from a wide ambit by the force of their own gravity, their fall towards the sun's centre must have engendered a vast thermal store, of which 453/454 are computed to be already spent. Presumably, however, this stream of reinforcement is still flowing. In the very act of parting with heat, the sun develops a fresh stock. His radiations, in short, are the direct result of shrinkage through cooling. A diminution of the solar diameter by 380 feet yearly would just suffice to cover the present rate of emission, and would for ages remain imperceptible with our means of observation, since, after the lapse of 6,000 years, the lessening of angular size would scarcely amount to one second.[1158] But the process, though not terminated, is strictly a terminable one. In less than five million years, the sun will have contracted to half its present bulk. In seven million more, it will be as dense as the earth. It is difficult to believe that it will then be a luminous body.[1159] Nor can an unlimited past duration be admitted. Helmholtz considered that radiation might have gone on with its actual intensity for twenty-two, Langley allows only eighteen million years. The period can scarcely be stretched, by the most generous allowances, to double the latter figure. But this is far from meeting the demands of geologists and biologists.

An attempt was made in 1881 to supply the sun with machinery analogous to that of a regenerative furnace, enabling it to consume the same fuel over and over again, and so to prolong indefinitely its beneficent existence. The inordinate "waste" of energy, which shocks our thrifty ideas, was simultaneously abolished. The earth stops and turns variously to account one 2,250-millionth part of the solar radiations; each of the other planets and satellites takes a proportionate share; the rest, being all but an infinitesmal fraction of the whole, is dissipated through endless space, to serve what purpose we know not. Now, on the late Sir William Siemens's plan, this reckless expenditure would cease; the solar incomings and outgoings would be regulated on approved economic principles, and the inevitable final bankruptcy would be staved off to remote ages.

But there was a fatal flaw in its construction. He imagined a perpetual circulation of combustible materials, alternately surrendering and regaining chemical energy, the round being kept going by the motive force of the sun's rotation.[1160] This, however, was merely to perch the globe upon a tortoise, while leaving the tortoise in the air. The sun's rotation contains a certain definite amount of mechanical power—enough, according to Lord Kelvin, if directly converted into heat, to keep up the sun's emission during 116 years and six days—a mere moment in cosmical time. More economically applied, it would no doubt go farther. Its exhaustion would, nevertheless, under the most favourable circumstances, ensue in a comparatively short period.[1161] Many other objections equally unanswerable have been urged to the "regenerative" hypothesis, but this one suffices.

Dr. Croll's collision hypothesis[1162] is less demonstrably unsound, but scarcely less unsatisfactory. By the mutual impact of two dark masses rushing together with tremendous speed, he sought to provide the solar nebula with an immense *original* stock of heat for the reinforcement of that subsequently evolved in the course of its progressive contraction. The sun, while still living on its capital, would thus have a larger capital to live on, and the time-demands of the less exacting geologists and biologists might be successfully met. But the primitive event, assumed for the purpose of dispensing them from the inconvenience of "hurrying up their phenomena," is not one that a sane judgment can readily admit to have ever, in point of actual fact, happened.

There remains, then, as the only intelligible rationale of solar sustentation, Helmholtz's shrinkage theory. And this has a very important bearing upon the nebular view of planetary formation; it may, in fact, be termed its complement. For it involves the idea that the sun's materials, once enormously diffused, gradually condensed to their present volume with development of heat and light, and, it may plausibly be added, with the separation of dependent globes. The data furnished by spectrum analysis, too, favour the supposition of a common origin for sun and planets by showing their community of substance; while gaseous nebulæ present examples of vast masses of tenuous vapour, such as our system may plausibly be conjectured to have primitively sprung from.

But recent science raises many objections to the details, if it supplies some degree of confirmation to the fundamental idea of Laplace's cosmogony. The detection of the retrograde movement of Neptune's satellite made it plain that the anomalous conditions of the Uranian world were due to no extraordinary disturbance, but to a systematic variety of arrangement at the outskirts of the solar domain. So that, were a trans-Neptunian planet discovered, we should be fully prepared to find it rotating, and surrounded by satellites circulating from east to west. The uniformity of movement, upon the probabilities connected with which the French geometer mainly based his scheme, thus at once vanishes.

The excessively rapid revolution of the inner Martian moon is a further stumbling-block. On Laplace's view, *no* satellite can revolve in a shorter time than its primary rotates; for in its period of circulation survives the period of rotation of the parent mass which filled the sphere of its orbit at the time of giving it birth. And rotation quickens as contraction goes on; therefore, the older time of axial rotation should invariably be the longer. This obstacle can, however, as we shall presently see, be turned.

More serious is one connected with the planetary periods, pointed out by Babinet in 1861.[1163] In order to make them fit in with the hypothesis of successive separation from a rotating and contracting body, certain arbitrary assumptions have to be made of fluctuations in the distribution of the matter forming that body at the various epochs of separation.[1164] Such expedients usually merit the distrust which they inspire. Primitive and permanent irregularities of density in the solar nebula, such as Miss Young's calculations suggest,[1165] do not, on the other hand, appear intrinsically improbable.

Again, it was objected by Professor Kirkwood in 1869[1166] that there could be no sufficient cohesion in such an enormously diffused mass as the planets are supposed to have sprung from to account for the wide intervals between them. The matter separated through the growing excess of centrifugal speed would have been cast off, not by rarely recurring efforts, but continually, fragmentarily, *pari passu* with condensation and acceleration. Each wisp of nebula, as it found itself unduly hurried, would have declared its independence, and set about revolving and condensing on its own account. The result would have been a meteoric, not a planetary system.

Moreover, it is a question whether the relative ages of the planets do not follow an order just the reverse of that concluded by Laplace. Professor Newcomb holds the opinion that the rings which eventually constituted the planets divided from the main body of the nebula almost simultaneously, priority, if there were any, being on the side of the inner and smaller ones;[1167] while in M. Faye's cosmogony,[1168] the retrograde motion of the systems formed by the two outer planets is ascribed—on grounds, it is true, of dubious validity—to their comparatively late origin.

This ingenious scheme was designed, not merely to complete, but to supersede that of Laplace, which, undoubtedly, through the inclusion by our system of oppositely directed rotations, forfeits its claim simply and singly to account for the fundamental peculiarities of its structure.

M. Faye's leading contention is that, under the circumstances assumed by Laplace, not the two outer planets alone, but the whole company must have been possessed of retrograde rotation. For they were formed—*ex hypothesi*—after the sun; central condensation had reached an advanced stage when the rings they were derived from separated; the principle of inverse squares consequently held good, and Kepler's Laws were in full operation. Now, particles circulating in obedience to these laws can only—since their velocity decreases outward from the centre of attraction—coalesce into a globe with a *backward* axial movement. Nor was Laplace blind to this flaw in his theory; but his effort to remove it, though it passed muster for the best part of a century,[1169] was scarcely successful. His planet-forming rings were made to rotate *all in one piece*, their outer parts thus necessarily travelling at a swifter linear rate than their inner parts, and eventually uniting, equally of necessity, into a *forward*-spinning body. The strength of cohesion involved may, however, safely be called impossible, especially when it is considered that nebulous materials were in question.

The reform proposed by M. Faye consists in admitting that all the planets inside Uranus are of pre-solar origin—that they took globular form in the bosom of a nearly homogeneous nebula, revolving in a single period, with motion accelerated from centre to circumference, and hence agglomerating into masses with a direct rotation. Uranus and Neptune owe their exceptional characteristics to their later birth. When they came into existence, the development of the sun was already far advanced, central force had acquired virtually its present strength, unity of period had been abolished by its predominance, and motion was retarded outward.

Thus, what we may call the relative chronology of the solar system is thrown once more into confusion. The order of seniority of the planets is now no easier to determine than the "Who first, who last?" among the victims of Hector's spear. For M. Faye's arrangements, notwithstanding the skill with which he has presented them, cannot be unreservedly accepted. The objections to them, thoughtfully urged by M. C. Wolf[1170] and Professor Darwin,[1171] are grave. Not the least so is his omission to take account of an agency of change presently to be noticed.

A further valuable discussion of the matter was published by M. du Ligondès in 1897.[1172] His views are those of Faye, modified to disarm the criticisms they had encountered; and special attention may be claimed for his weighty remark that each planet has a life-history of its own, essentially distinct from those of the others, and, despite original unity, not to be confounded with them. The drift of recent investigations seems, indeed, to be to find the embryonic solar system already potentially complete in the parent nebula, like the oak in an acorn, and to relegate detailed explanations of its peculiarities to the dim pre-nebular fore-time.

We now come to a most remarkable investigation—one, indeed, unique in its profession to lead us back with mathematical certainty towards the origin of a heavenly body. We refer to Professor Darwin's inquiries into the former relations of the earth and moon.[1173]

They deal exclusively with the effects of tidal friction, and primarily with those resulting, not from oceanic, but from "bodily" tides, such as the sun and moon must have raised in past ages on a liquid or viscous earth. The immediate effect of either is, as already explained, to destroy the rotation of the body on which the tide is raised, as regards the tide-raising body, bringing it to turn always the same face towards its disturber. This, we can see, has been completely brought about in the case of the moon. There is, however, a secondary or reactive effect. Action is always mutual. Precisely as much as the moon pulls the terrestrial tidal wave backward, the tidal wave pulls the moon forward. But pulling a body forward in its orbit implies the enlargement of that orbit; in other words, the moon is, as a consequence of tidal friction, very slowly receding from the earth. This will go on (other circumstances remaining unchanged) until the lengthening day overtakes the more tardily lengthening month, when each will be of about 1,400 hours.[1174] A position of what we may call tidal equilibrium between earth and moon will (apart from disturbance by other bodies) then be attained.

If, however, it be true that, in the time to come, the moon will be much farther from us, it follows that in the time past she was much nearer to us than she now is. Tracing back her history by the aid of Professor Darwin's clue, we at length find her revolving in a period of somewhere between two and four hours, almost in contact with an earth rotating just at the same rate. This was before tidal friction had begun its work of grinding down axial velocity and expanding orbital range. But the position was not one of stable equilibrium. The slightest inequality must have set on foot a series of uncompensated changes. If the moon had whirled the least iota faster than the earth spun she must have been precipitated upon it. Her actual existence shows that the trembling balance inclined the other way. By a second or two to begin with, the month exceeded the day; the tidal wave crept ahead of the moon; tidal friction came into play, and our satellite started on its long spiral journey outward from the parent globe. This must have occurred, it is computed, *at least* fifty-four million years ago.

That this kind of tidal reactive effect played its part in bringing the moon into its present position, and is still, to some slight extent, at work in changing it, there can be no doubt whatever. An irresistible conjecture carried the explorer of its rigidly deducible consequences one step beyond them. The moon's time of revolution, when so near the earth as barely to escape contact with it, must have been, by Kepler's Law, more than two and less than two and a half hours. Now it happens that the most rapid rate of rotation of a fluid mass of the earth's average density, consistent with spheroidal equilibrium, is two hours and twenty minutes. Quicken the movement but by one second and the globe must fly asunder. Hence the inference that the earth actually *did* fly asunder through over-fast spinning, the ensuing disruption representing the birth-throes of the moon. It is likely that the event was hastened or helped by solar tidal disturbance.

To recapitulate. Analysis tracks backward the two bodies until it leaves them in very close contiguity, one rotating and the other revolving in approximately the same time, and that time certainly not far different from, and quite possibly identical with, the critical period of instability for the terrestrial spheroid. "Is this," Professor Darwin asks, "a mere coincidence, or does it not rather point to the break-up of the primeval planet into two masses in consequence of a too rapid rotation?"[1175]

We are tempted, but are not allowed to give an unqualified assent. Mr. James Nolan of Victoria has made it clear that the moon could not have subsisted as a continuous mass under the powerful disruptive strain which would have acted upon it when revolving almost in contact with the present surface of the earth; and Professor Darwin, admitting the objection, concedes to our satellite, in its initial stage, the alternative form of a flock of meteorites.[1176] But such a congregation must have been quickly dispersed, by tidal action, into a meteoric ring. The same investigator subsequently fixed 6,500 miles from centre to centre as the minimum distance at which the moon could have revolved in its entirety; and he concluded it "necessary to suppose that, after the birth of a satellite, if it takes place at all in this way, a series of changes occur which are quite unknown."[1177] The evidence, however, for the efficiency of tidal friction in bringing about the actual configuration of the lunar-terrestrial system is not invalidated by this failure to penetrate its natal mystery. Under its influence the principal elements of that system fall into interdependent mutual relations. It connects, casually and quantitatively, the periods of the moon's revolution and of the earth's rotation, the obliquity of the ecliptic, the inclination and eccentricity of the lunar orbit. All this can scarcely be accidental.

Professor Darwin's first researches on this subject were communicated to the Royal Society, December 18, 1879. They were followed, January 20, 1881,[1178] by an inquiry on the same principles into the earlier condition of the entire solar system. The results were a warning against hasty generalisation. They showed that the lunar-terrestrial system, far from being a pattern for their development, was a singular exception among the bodies swayed by the sun. Its peculiarity resides in the fact that the moon is *proportionately* by far the most massive attendant upon any known planet. Its disturbing power over its primary is thus abnormally great, and tidal friction has, in consequence, played a predominant part in bringing their mutual relations into their present state.

The comparatively late birth of the moon tends to ratify this inference. The dimensions of the earth did not differ (according to our present authority) very greatly from what they now are when her solitary offspring came, somehow, into existence. This is found not to have been the case with any other of the planets. It is unlikely that the satellites of Jupiter, Saturn, or Mars (we may safely add, of Uranus or Neptune) ever revolved in much narrower orbits than those they now traverse; it is practically certain that they did not, like our moon, originate very near the *present* surfaces of their primaries.[1179] What follows? The tide-raising power of a body grows with vicinity in a rapidly accelerated ratio. Lunar tides must then have been on an enormous scale when the moon swung round at a fraction of its actual distance from the earth. But no other satellite with which we are acquainted occupied at any time a corresponding position. Hence no other satellite ever possessed tide-raising capabilities in the least comparable to those of the moon. We conclude once more that tidal friction had an influence here very different from its influence elsewhere. Quite possibly, however, that influence may be more nearly spent than in less advanced combinations of revolving globes. Mr. Nolan concluded in 1895[1180] that it still retains appreciable efficacy in the several domains of the outer planets. The moons of Jupiter and Saturn are, by his calculations, in course of sensible retreat, under compulsion of the perennial ripples raised by them on the surfaces of their gigantic primaries. He thus connects the interior position of the fifth Jovian satellite with its small mass. The feebleness of its tide-raising power obliged it to remain behind its companions; for there is no sign of its being more juvenile than the Galilean quartette.

The yielding of plastic bodies to the strain of unequal attractions is a phenomenon of far-reaching consequence. We know that the sun as well as the moon causes tides in our oceans. There must, then, be solar, no less than lunar, tidal friction. The question at once arises: What part has it played in the development of the solar system? Has it ever been one of leading importance, or has its influence always been, as it now is, subordinate, almost negligible? To this, too, Professor Darwin supplies an answer.

It can be stated without hesitation that the sun did *not* give birth to the planets, as the earth has been supposed to have given birth to the moon, by the disruption of its already condensed, though viscous and glowing mass, pushing them then gradually backward from its surface into their present places. For the utmost possible increase in the length of the year through tidal friction is one hour; and five minutes is a more probable estimate. [1181] So far as the pull of tide-waves raised on the sun by the planets is concerned, then, the distances of the latter have never been notably different from what they now are; though that cause may have converted the paths traversed by them from circles into ellipses.

Over their *physical* history, however, it was probably in a large measure influential. The first vital issue for each of them was—satellites or no satellites? Were they to be governors as well as governed, or should they revolve in sterile isolation throughout the æons of their future existence? Here there is strong reason to believe that solar tidal friction was the overruling power. It is remarkable that planetary fecundity increases—at least so far outward as Saturn—with distance from the sun. Can these two facts be in any way related? In other words, is there any conceivable way by which tidal influence could prevent or impede the throwingoff of secondary bodies? We have only to think for a moment in order to see that this is precisely one of its direct results.[1182]

Tidal friction, whether solar or lunar, tends to reduce the axial movement of the body it acts upon. But the separation of satellites depends—according to the received view—upon the attainment of a disruptive rate of rotation. Hence, if solar tidal friction were strong enough to keep down the pace below this critical point, the contracting mass would remain intact—there would be no satellite-production. This, in all probability, actually occurred in the case both of Mercury and Venus. They cooled without dividing, because the solar friction-brake applied to them was too strong to permit acceleration to pass the limit of equilibrium. The complete destruction of their relative axial movement has been rendered probable by recent observations; and that the process went on rapidly is a reasonable further inference. The earth barely escaped the fate of loneliness incurred by her neighbours. Her first and only epoch of instability was retarded until she had nearly reached maturity. The late appearance of the moon accounts for its large relative size—through the increased cohesion of an already strongly condensed parent mass—and for the distinctive peculiarities of its history and influence on the producing globe.

Solar tidal friction, although it did not hinder the formation of two minute dependents of Mars, has been invoked to explain the anomalously rapid revolution of one of them. Phobos, we have seen, completes more than three revolutions while Mars rotates once. But this was probably not always so. The two periods were originally nearly equal. The difference, it is alleged, was brought about by tidal waves raised by the sun on the semi-fluid spheroid of Mars. Rotatory velocity was thereby destroyed, the Martian day slowly lengthened, and, as a secondary consequence, the period of the inner satellite, become shorter than the augmented day, began progressively to diminish. So that Phobos, unlike our moon, was in the beginning farther from its primary than now.

But here again Mr. Nolan entered a *caveat*. Applying the simple test of numerical evaluation, he showed that before solar tidal friction could lengthen the rotation-period of Mars by so much as one minute, Phobos should have been precipitated upon its surface.[1183] For the enormous disparity of mass between it and the sun is so far neutralised by the enormous disparity in their respective distances from Mars that solar tidal force there is only fifty times that of the little satellite. But the tidal effects of a satellite circulating quicker than its primary rotates exactly reverse those of one moving, like our moon, comparatively slowly, so that the tides raised by Phobos tend to *shorten* both periods. Its orbital momentum, however, is so extremely small in proportion to the rotational momentum of Mars, that any perceptible inroad upon the latter is attended by a lavish and ruinous expenditure of the former. It is as if a man owning a single five-pound note were to play for equal stakes with a man possessing a million. The bankruptcy sure to ensue is typified by the coming fate of the Martian inner satellite. The catastrophe of its fall needs to bring it about only a very feeble reactive pull compared with the friction which the sun should apply in order to protract the Martian day by one minute. And from the proportionate strength of the forces at work, it is quite certain that one result cannot take place without the other. Nor can things have been materially different in the past; hence the idea must be abandoned that the primitive time of rotation of Mars survives in the period of its inner satellite.

The anomalous shortness of the latter may, however, in M. Wolf's opinion,[1184] be explained by the "traînées elliptiques" with which Roche supplemented nebular annulation.[1185] These are traced back to the descent of separating strata from the *shoulders* of the great nebulous spheroid towards its equatorial plane. Their rotational velocity being thus relatively small, they formed "inner rings," very much nearer to the centre of condensation than would have been possible on the unmodified theory of Laplace. Phobos might, in this view, be called a polar offset of Mars; and the rings of Saturn are thought to own a similar origin.

Outside the orbit of Mars, solar tidal friction can scarcely be said to possess at present any sensible power. But it is far from certain that this was always so. It seems not unlikely that its influence was the overruling one in determining the direction of planetary rotation. M. Faye, as we have seen, objected to Laplace's scheme that only retrograde secondary systems could be produced by it. In this he was anticipated by Kirkwood, who, however, supplied an answer to his own objection.[1186]

Sun-raised tides must have acted with great power on the diffused masses of the embryo planets. By their means they doubtless very soon came to turn (in lunar fashion) the same hemisphere always towards their centre of motion. This amounts to saying that even if they started with retrograde rotation, it was, by solar tidal friction, quickly rendered direct.[1187] For it is scarcely necessary to point out that a planet turning an invariable face to the sun rotates in the same direction in which it revolves, and in the same period. As, with the progress of condensation, tides became feebler and rotation more rapid, the accelerated spinning necessarily proceeded in the sense thus prescribed for it. Hence the backward axial movements of Uranus and Neptune may very well be a survival, due to the inefficiency of solar tides at their great distance, of a state of things originally prevailing universally throughout the system.

The general outcome of Mr. Darwin's researches has been to leave Laplace's cosmogony untouched. He concludes nothing against it, and, what perhaps tells with more weight in the long run, has nothing to substitute for it. In one form or the other, if we speculate at all on the development of the planetary system, our speculations are driven into conformity with the broad lines of the Nebular Hypothesis—to the extent, at least, of admitting an original material unity and motive uniformity. But we can see now, better than formerly, that these supply a bare and imperfect sketch of the truth. We should err gravely were we to suppose it possible to reconstruct, with the help of any knowledge our race is ever likely to possess, the real and complete history of our admirable system. "The subtlety of nature," Bacon says, "transcends in many ways the subtlety of the intellect and senses of man." By no mere barren formula of evolution, indiscriminately applied all round, the results we marvel at, and by a fragment of which our life is conditioned, were brought forth; but by the manifold play of interacting forces, variously modified and variously prevailing, according to the local requirements of the design they were appointed to execute.

FOOTNOTES:

[1150] *Exposition du Système du Monde*, t. ii., p. 295.

[1151] In later editions a retrospective clause was added admitting a prior condition of all but evanescent nebulosity.

[1152] *Méc. Cél.*, lib. xiv., ch. iii.

[1153] *Beiträge zur Dynamik des Himmels*, p. 12.

[1154] *Trans. Roy. Soc. of Edinburgh*, vol. xxi., p. 66.

[1155] Newcomb, *Pop. Astr.*, p. 521 (2nd ed.).

[1156] M. Williams, *Nature*, vol. iii., p. 26.

[1157] *Comp. Brit. Almanac*, p. 94.

[1158] Radau, *Bull. Astr.*, t. ii., p. 316.

[1159] Newcomb, *Pop. Astr.*, pp. 521-525.

[1160] *Proc. Roy. Soc.*, vol. xxxiii., p. 393.

[1161] To this hostile argument, as urged by Mr. E. Douglas Archibald, Sir W. Siemens opposed the increase of rotative velocity through contraction (*Nature*, vol. xxv., p. 505). But contraction cannot restore lost momentum.

[1162] *Stellar Evolution, and its Relations to Geological Time*, 1889.

[1163] *Comptes Rendus*, t. lii., p. 481. See also Kirkwood, *Observatory*, vol. iii., p. 409.

[1164] Fouché, *Comptes Rendus*, t. xcix., p. 903.

[1165] *Astroph. Jour.*, vol. xiii., p. 338.

[1166] *Month. Not.*, vol. xxix., p. 96.

[1167] *Pop. Astr.*, p. 257.

[1168] *Sur l'Origine du Monde*, 1884.

[1169] Kirkwood adverted to it in 1864, *Am. Jour.*, vol. xxxviii., p. 1.

[1170] *Bull. Astr.*, t. ii.

[1171] *Nature*, vol. xxxi., p. 506.

[1172] *Formation Mécanique du Système du Monde; Bull. Astr.*, t. xiv., p. 313 (O. Callandreau). See also, *Le Problème Solaire*, by l'Abbé Th. Moreux, 1900.

[1173] *Phil. Trans.*, vol. clxxi., p. 713.

[1174] Mr. J. Nolan has pointed out (*Nature*, vol. xxxiv., p. 287) that the length of the equal day and month will be reduced to about 1,240 hours by the effects of *solar* tidal friction.

[1175] *Phil. Trans.*, vol. clxxi., p. 835.

[1176] *Nature*, vol. xxxiii., p. 368; see also Nolan, *Ibid.*, vol. xxxiv., p. 286.

[1177] *Phil. Trans.*, vol. clxxviii., p. 422.

[1178] *Ibid.*, vol. clxxii., p. 491.

[1179] *Ibid.*, p. 530.

[1180] *Satellite Evolution*, Melbourne, 1895; *Knowledge*, vol. xviii., p. 205.

[1181] *Phil. Trans.*, vol. clxxii., p. 533.

[1182] This was perceived by M. Ed. Roche in 1872. *Mém. de l'Acad. des Sciences de Montpellier*, t. viii., p. 247.

[1183] *Nature*, vol. xxxiv., p. 287.

[1184] *Bull. Astr.*, t. ii., p. 223.

[1185] *Montpellier Méms.*, t. viii., p. 242.

[1186] *Amer. Jour.*, vol. xxxviii. (1864), p. 1.

[1187] Wolf, *Bull. Astr.*, t. ii., p. 76.

CHAPTER X

RECENT COMETS

On the 2nd of June, 1858, Giambattista Donati discovered at Florence a feeble round nebulosity in the constellation Leo, about one-tenth the diameter of the full moon. It proved to be a comet approaching the sun. But it changed little in apparent place or brightness for some weeks. The gradual development of a central condensation of light was the first symptom of coming splendour. At Harvard, in the middle of July, a strong stellar nucleus was seen; on August 14 a tail began to be thrown out. As the comet wanted still over six weeks of the time of its perihelion-passage, it was obvious that great things might be expected of it. They did not fail of realisation.

Not before the early days of September was it generally recognised with the naked eye, though it had been detected without a glass at Pulkowa, August 19. But its growth was thenceforward surprisingly rapid, as it swept with accelerated motion under the hindmost foot of the Great Bear, and past the starry locks of Berenice. A sudden leap upward in lustre was noticed on September 12, when the nucleus shone with about the brightness of the pole-star, and the tail, notwithstanding large foreshortening, could be traced with the lowest telescopic power over six degrees of the sphere. The appendage, however, attained its full development only after perihelion, September 30, by which time, too, it lay nearly square to the line of sight from the earth. On October 10 it stretched in a magnificent scimitar-like curve over a third and upwards of the visible hemisphere, representing a real extension in space of fifty-four million miles. But the most striking view was presented on October 5, when the brilliant star Arcturus became involved in the brightest part of the tail, and during many hours contributed, its lustre undiminished by the interposed nebulous screen, to heighten the grandeur of the most majestic celestial object of which living memories retain the impress. Donati's comet was, according to Admiral Smyth's testimony,[1188] outdone "as a mere *sight*-object" by the great comet of 1811; but what it lacked in splendour, it surely made up in grace, and variety of what we may call "scenic" effects.

Some of these were no less interesting to the student than impressive to the spectator. At Pulkowa, on the 16th September, Winnecke,[1189] the first director of the Strasburg Observatory, observed a faint outer envelope resembling a veil of almost evanescent texture flung somewhat widely over the head. Next evening, the first of the "secondary" tails appeared, possibly as part of the same phenomenon. This was a narrow straight ray, forming a tangent to the strong curve of the primary tail, and reaching to a still greater distance from the nucleus. It continued faintly visible for about three weeks, during part of which time it was seen in duplicate. For from the chief train itself, at a point where its curvature abruptly changed, issued, as if through the rejection of some of its materials, a second beam nearly parallel to the first, the rigid line of which contrasted singularly with the softly diffused and waving aspect of the plume of light from which it sprang. Olbers's theory of unequal repulsive forces was never more beautifully illustrated. The triple tail seemed a visible solar analysis of cometary matter.

The processes of luminous emanation going on in this body forcibly recalled the observations made on the comets of 1744 and 1835. From the middle of September, the nucleus, estimated by Bond to be under five hundred miles in diameter, was the centre of action of the most energetic kind. Seven distinct "envelopes" were detached in succession from the nebulosity surrounding the head, and after rising towards the sun during periods of from four to seven days, finally cast their material backward to form the right and left branches of the great train. The separation of these by an obscure axis—apparently as black, quite close up to the nucleus, as the sky—indicated for the tail a hollow, cone-like structure;[1190] while the repetition of certain spots and rays in the same corresponding situation on one envelope after another served to show that the nucleus—to some local peculiarity of which they were doubtless due—had no proper rotation, but merely shifted sufficiently on an axis to preserve the same aspect towards the sun as it moved round it.[1191] This observation of Bond's was strongly confirmatory of Bessel's hypothesis of opposite polarities in such bodies' opposite sides.

The protrusion towards the sun, on September 25, of a brilliant luminous fan-shaped sector completed the resemblance to Halley's comet. The appearance of the head was now somewhat that of a "bat's-wing" gaslight. There were, however, no oscillations to and fro, such as Bessel had seen and speculated upon in 1835. As the size of the nucleus contracted with approach to perihelion, its intensity augmented. On October 2, it outshone Arcturus, and for a week or ten days was a conspicuous object half an hour after sunset. Its lustre—setting aside the light derived from the tail—was, at that date, 6,300 times what it had been on June 15, though *theoretically*—taking into account, that is, only the differences of distance from sun and earth—it should have been only 1/33 of that amount. Here, it might be thought, was convincing evidence of the comet itself becoming ignited under the growing intensity of the solar radiations. Yet experiments with the polariscope were interpreted in an adverse sense, and Bond's conclusion that the comet sent us virtually unmixed reflected sunshine was generally acquiesced in. It was, nevertheless, negatived by the first application of the spectroscope to these bodies.

Very few comets have been so well or so long observed as Donati's. It was visible to the naked eye during 112 days; it was telescopically discernible for 275, the last observation having been made by Mr. William Mann at the Cape of Good Hope, March 4, 1859. Its course through the heavens combined singularly with the orbital place of the earth to favour curious inspection. The tail, when near its greatest development, lost next to nothing by the effects of perspective, and at the same time lay in a plane sufficiently inclined to the line of sight to enable it to display its exquisite curves to the greatest advantage. Even the weather was, on both sides of the Atlantic, propitious during the period of greatest interest, and the moon as little troublesome as possible. The volume compiled by the younger Bond is a monument to the care and skill with which these advantages were turned to account. Yet this stately apparition marked no turning-point in the history of cometary science. By its study knowledge was indeed materially advanced, but along the old lines. No quick and vivid illumination broke upon its path. Quite insignificant objects—as we have already partly seen—have often proved more vitally instructive.

Donati's comet has been identified with no other. Its path is an immensely elongated ellipse, lying in a plane far apart from that of the planetary movements, carrying it at perihelion considerably within the orbit of Venus, and at aphelion out into space to 5-1/2 times the distance from the sun of Neptune. The entire circuit occupies over 2,000 years, and is performed in a retrograde direction, or against the order of the Signs. Before its next return, about the year 4000 A.D., the enigma of its presence and its purpose may have been to some extent—though we may be sure not completely—penetrated.

On June 30, 1861, the earth passed, for the second time in the century, through the tail of a great comet. Some of our readers may remember the unexpected disclosure, on the withdrawal of the sun below the horizon on that evening, of an object so remarkable as to challenge universal attention. A golden-yellow planetary disc, wrapt in dense nebulosity, shone out while the June twilight of these latitudes was still in its first strength. The number and complexity of the envelopes surrounding the head produced, according to the late Mr. Webb,[1192] a magnificent effect. Portions of six distinct emanations were traceable. "It was as though a number of light, hazy clouds were floating round a miniature full moon." As the sky darkened the tail emerged to view.[1193] Although in brightness and sharpness of definition it could not compete with the display of 1858, its dimensions proved to be extraordinary. It reached upwards beyond the zenith when the head had already set. By some authorities its extreme length was stated at 118°, and it showed no trace of curvature. Most remarkable, however, was the appearance of two widely divergent rays, each pointing towards the head, though cut off from it by sky-illumination, of which one was seen by Mr. Webb, and both by Mr. Williams at Liverpool, a quarter of an hour before midnight. There seems no doubt that Webb's interpretation was the true one, and that these beams were, in fact, "the perspective representation of a conical or cylindrical tail, hanging closely above our heads, and probably just being lifted up out of our atmosphere."[1194] The cometary train was then rapidly receding from the earth, so that the sides of the "outspread fan" of light shown by it when we were right in the line of its axis must have appeared (as they did) to close up in departure. The swiftness with which the visually opened fan shut proved its vicinity; and, indeed, Mr. Hind's calculations showed that we were not so much near as actually within its folds at that very time.

Already M. Liais, from his observations at Rio de Janeiro, June 11 to 14, and Mr. Tebbutt, by whom the comet was discovered in New South Wales on May 13, had anticipated such an encounter, while the former subsequently proved that it must have occurred in such a way as to cause an immersion of the earth in cometary matter to a depth of 300,000 miles.[1195] The comet then lay between the earth and the sun at a distance of about fourteen million miles from the former; its tail stretched outward just along the line of intersection of its own with the terrestrial orbit to an extent of fifteen million miles; so that our globe, happening to pass at the time, found itself during some hours involved in the flimsy appendage.

No perceptible effects were produced by the meeting; it was known to have occurred by theory alone. A peculiar glare in the sky, thought by some to have distinguished the evening of June 30, was, at best, inconspicuous. Nor were there any symptoms of unusual electric excitement. The Greenwich instruments were, indeed, disturbed on the following night, but it would be rash to infer that the comet had art or part in their agitation.

The perihelion-passage of this body occurred June 11, 1861; and its orbit has been shown by M. Kreutz of Bonn, from a very complete investigation founded on observations extending over nearly a year, to be an ellipse traversed in a period of 409 years.[1196]

Towards the end of August, 1862, a comet became visible to the naked eye high up in the northern hemisphere, with a nucleus equalling in brightness the lesser stars of the Plough and a feeble tail 20° in length. It thus occupied quite a secondary position among the members of its class. It was, nevertheless, a splendid object in comparison with a telescopic nebulosity discovered by Tempel at Marseilles, December 19, 1865. This, the sole comet of 1866, slipped past perihelion, January 11, without pomp of train or other appendages, and might have seemed hardly worth the trouble of pursuing. Fortunately, this was not the view entertained by observers and computers; since upon the knowledge acquired of the movements of these two bodies has been founded one of the most significant discoveries of modern times. The first of them is now styled the comet (1862 iii.) of the August meteors, the second (1866 i.) that of the November meteors. The steps by which this curious connection came to be ascertained were many, and were taken in succession by a number of individuals. But the final result was reached by Schiaparelli of Milan, and remains deservedly associated with his name.

The idea prevalent in the eighteenth century as to the nature of shooting stars was that they were mere aerial *ignes fatui*—inflammable vapours accidentally kindled in our atmosphere. But Halley had already entertained the opinion of their cosmical origin; and Chladni in 1794 formally broached the theory that space is filled with minute circulating atoms, which, drawn by the earth's attraction, and ignited by friction in its gaseous envelope, produce the luminous effects so frequently witnessed.[1197] Acting on his suggestion, Brandes and Benzenberg, two students at the University of Göttingen, began in 1798 to determine the heights of falling stars by simultaneous observations at a distance. They soon found that they move with planetary velocities in the most elevated regions of our atmosphere, and by the ascertainment of this fact laid a foundation of distinct knowledge regarding them. Some of the data collected, however, served only to perplex opinion, and even caused Chladni temporarily to renounce his. Many high authorities, headed by Laplace in 1802, declared for the lunar-volcanic origin of meteorites; but thought on the subject was turbid, and inquiry seemed only to stir up the mud of ignorance. It needed one of those amazing spectacles, at which man assists, no longer in abject terror for his own frail fortunes, but with keen curiosity and the vivid expectation of new knowledge, to bring about a clarification.

On the night of November 12-13, 1833, a tempest of falling stars broke over the earth. North America bore the brunt of its pelting. From the Gulf of Mexico to Halifax, until daylight with some difficulty put an end to the display, the sky was scored in every direction with shining tracks and illuminated with majestic fireballs. At Boston the frequency of meteors was estimated to be about half that of flakes of snow in an average snowstorm. Their numbers, while the first fury of their coming lasted, were quite beyond counting; but as it waned, a reckoning was attempted, from which it was computed, on the basis of that much diminished rate, that 240,000 must have been visible during the nine hours they continued to fall.[1198]

Now there was one very remarkable feature common to the innumerable small bodies which traversed, or were consumed in our atmosphere that night. *They all seemed to come from the same part of the sky.* Traced backward, their paths were invariably found to converge to a point in the constellation Leo. Moreover, that point travelled with the stars in their nightly round. In other words, it was entirely independent of the earth and its rotation. It was a point in inter-planetary space.

The *effective* perception of this fact[1199] amounted to a discovery, as Olmsted and Twining, who had “simultaneous ideas” on the subject, were the first to realize. Denison Olmsted was then Professor of Mathematics in Yale College. He showed early in 1834[1200] that the emanation of the showering meteors from a fixed “radiant” proved their approach to the earth along nearly parallel lines, appearing to diverge by an effect of perspective; and that those parallel lines must be sections of orbits described by them round the sun and intersecting that of the earth. For the November phenomenon was now seen to be a periodical one. On the same night of the year 1832, although with less dazzling and universal splendour than in America in 1833, it had been witnessed over great part of Europe and in Arabia. Olmsted accordingly assigned to the cloud of cosmical particles (or “comet,” as he chose to call it), by terrestrial encounters with which he supposed the appearances in question to be produced, a period of about 182 days; its path a narrow ellipse, meeting, near its farthest end from the sun, the place occupied by the earth on November 12.

Once for all, then, as the result of the star-fall of 1833, the study of luminous meteors became an integral part of astronomy. Their membership of the solar system was no longer a theory or a conjecture—it was an established fact. The discovery might be compared to, if it did not transcend in importance, that of the asteroidal group. “C’est un nouveau monde planétaire,” Arago wrote,[1201] “qui commence à se révéler à nous.”

Evidences of periodicity continued to accumulate. It was remembered that Humboldt and Bonpland had been the spectators at Cumana, after midnight on November 12, 1799, of a fiery shower little inferior to that of 1833, and reported to have been visible from the equator to Greenland. Moreover, in 1834 and some subsequent years, there were waning repetitions of the display, as if through the gradual thinning-out of the meteoric supply. The extreme irregularity of its distribution was noted by Olbers in 1837, who conjectured that we might have to wait until 1867 to see the phenomenon renewed on its former scale of magnificence.[1202] This was the first hint of a thirty-three or thirty-four year period.

The falling stars of November did not alone attract the attention of the learned. Similar appearances were traditionally associated with August 10 by the popular phrase in which they figured as “the tears of St. Lawrence.” But the association could not be taken on trust from mediæval authority. It had to be proved scientifically, and this Quetelet of Brussels succeeded in doing in December, 1836.[1203]

A second meteoric revolving system was thus shown to exist. But its establishment was at once perceived to be fatal to the “cosmical cloud” hypothesis of Olmsted. For if it be a violation of probability to attribute to one such agglomeration a period of an exact year, or sub-multiple of a year, it would be plainly absurd to suppose the movements of *two* or more regulated by such highly artificial conditions. An alternative was proposed by Adolf Erman of Berlin in 1839.[1204] No longer in *clouds*, but in closed *rings*, he supposed meteoric matter to revolve round the sun. Thus the mere circumstance of intersection by a meteoric of the terrestrial orbit, without any coincidence of period, would account for the earth meeting some members of the system at each annual passage through the “node” or point of intersection. This was an important step in advance, yet it decided nothing as to the forms of the orbits of such annular assemblages; nor was it followed up in any direction for a quarter of a century.

Hubert A. Newton took up, in 1864,[1205] the dropped thread of inquiry. The son of a mathematical mother, he attained, at the age of twenty-five, to the dignity of Professor of Mathematics in Yale University, and occupied the post until his death in 1896. The diversion of his powers, however, from purely abstract studies stimulated their effective exercise, and constituted him one of the founders of meteoric astronomy.

A search through old records carried the November phenomenon back to the year 902 A.D., long distinguished as “the year of the stars.” For in the same night in which Taormina was captured by the Saracens, and the cruel Aghlabite tyrant Ibrahim ibn Ahmed died “by the judgment of God” before Cosenza, stars fell from heaven in such abundance as to amaze and terrify beholders far and near. This was on October 13, and recurrences were traced down through the subsequent centuries, always with a day's delay in about seventy years. It was easy, too, to derive from the dates a cycle of 33-1/4 years, so that Professor Newton did not hesitate to predict the exhibition of an unusually striking meteoric spectacle on November 13-14, 1866.[1206]

For the astronomical explanation of the phenomena, recourse was had to a method introduced by Erman of computing meteoric orbits. It was found, however, that conspicuous recurrences every thirty-three or thirty-four years could be explained on the supposition of five widely different periods, combined with varying degrees of extension in the revolving group. Professor Newton himself gave the preference to the shortest—of 354-1/2 days, but indicated the means of deciding with certainty upon the true one. It was furnished by the advancing motion of the node, or that day's delay of the November shower every seventy years, which the old chronicles had supplied data for detecting. For this is a strictly measurable effect of gravitational disturbance by the various planets, the amount of which naturally depends upon the course pursued by the disturbed bodies. Here the great mathematical resources of Professor Adams were brought to bear. By laborious processes of calculation, he ascertained that four out of Newton's five possible periods were entirely incompatible with the observed nodal displacement, while for the fifth—that of 33-1/4 years—a perfectly harmonious result was obtained.[1207] This was the last link in the chain of evidence proving that the November meteors—or "Leonids," as they had by that time come to be called—revolve round the sun in a period of 33·27 years, in an ellipse spanning the vast gulf between the orbits of the earth and Uranus, the group being so extended as to occupy nearly three years in defiling past the scene of terrestrial encounters. But before it was completed in March, 1867, the subject had assumed a new aspect and importance.

Professor Newton's prediction of a remarkable star-shower in November, 1866, was punctually fulfilled. This time, Europe served as the main target of the celestial projectiles, and observers were numerous and forewarned. The display, although, according to Mr. Baxendell's memory,[1208] inferior to that of 1833, was of extraordinary impressiveness. Dense crowds of meteors, equal in lustre to the brightest stars, and some rivalling Venus at her best,[1209] darted from east to west across the sky with enormous apparent velocities, and with a certain determinateness of aim, as if let fly with a purpose, and at some definite object.[1210] Nearly all left behind them trains of emerald green or clear blue light, which occasionally lasted many minutes, before they shrivelled and curled up out of sight. The maximum rush occurred a little after one o'clock on the morning of November 14, when attempts to count were overpowered by frequency. But during a previous interval of seven minutes five seconds, four observers at Mr. Bishop's observatory at Twickenham reckoned 514, and during an hour 1,120.[1211] Before daylight the earth had fairly cut her way through the star-bearing stratum; the "ethereal rockets" had ceased to fly.

This event brought the subject of shooting stars once more vividly to the notice of astronomers. Schiaparelli had, indeed, been already attracted by it. The results of his studies were made known in four remarkable letters, addressed, before the close of the year 1866, to Father Secchi, and published in the *Bulletino* of the Roman Observatory.[1212] Their upshot was to show, in the first place, that meteors possess a real velocity considerably greater than that of the earth, and travel, accordingly, to enormously greater distances from the sun along tracks resembling those of comets in being very eccentric, in lying at all levels indifferently, and in being pursued in either direction. It was next inferred that comets and meteors equally have an origin foreign to the solar system, but are drawn into it temporarily by the sun's attraction, and occasionally fixed in it by the backward pull of some planet. But the crowning fact was reserved for the last. It was the astonishing one that the August meteors move in the same orbit with the bright comet of 1862—that the comet, in fact, is but a larger member of the family named "Perseids" because their radiant point is situated in the constellation Perseus.

This discovery was quickly capped by others of the same kind. Leverrier published, January 21, 1867,[1213] elements for the November swarm, founded on the most recent and authentic observations; at once identified by Dr. C. F. W. Peters of Altona with Oppolzer's elements for Tempel's comet of 1866.[1214] A few days later, Schiaparelli, having recalculated the orbit of the meteors from improved data, arrived at the same conclusion; while Professor Weiss of Vienna pointed to the agreement between the orbits of a comet which had appeared in 1861 and of a star-shower found to recur on April 20 (Lyraïds), as well as between those of Biela's comet and certain conspicuous meteors of November 28.[1215]

These instances do not seem to be exceptional. The number of known or suspected accordances of cometary tracks with meteor streams contained in a list drawn up in 1878[1216] by Professor Alexander S. Herschel (who has made the subject peculiarly his own) amounts to seventy-six; although the four first detected still remain the most conspicuous, and perhaps the only absolutely sure examples of a relation as significant as it was, to most astronomers, unexpected.

There had, indeed, been anticipatory ideas. Not that Kepler's comparison of shooting stars to "minute comets," or Maskelyne's "forse risulterà che essi sono comete," in a letter to the Abate Cesaris, December 12, 1774,[1217] need count for much. But Chladni, in 1819,[1218] considered both to be fragments or particles of the same primitive matter, irregularly scattered through space as nebulæ; and Morstadt of Prague suggested about 1837[1219] that the meteors of November might be dispersed atoms from the tail of Biela's comet, the path of which is cut across by the earth near that epoch. Professor Kirkwood, however, by a luminous intuition, penetrated the whole secret, so far as it has yet been made known. In an article published, or rather buried, in the *Danville Quarterly Review* for December, 1861, he argued, from the observed division of Biela, and other less noted instances of the same kind, that the sun exercises a "divellent influence" on the nuclei of comets, which may be presumed to continue its action until their corporate existence (so to speak) ends in complete pulverisation. “May not,” he continued, “our periodic meteors be the débris of ancient but now disintegrated comets, whose matter has become distributed round their orbits?”[1220]

The gist of Schiaparelli’s discovery could not be more clearly conveyed. For it must be borne in mind that with the ultimate destiny of comets’ tails this had nothing to do. The tenuous matter composing them is, no doubt, permanently lost to the body from which it emanated; but science does not pretend to track its further wanderings through space. It can, however, state categorically that these will no longer be conducted along the paths forsaken under solar compulsion. From the central, and probably solid parts of comets, on the other hand, are derived the granules by the swift passage of which our skies are seamed with periodic fires. It is certain that a loosely agglomerated mass (such as cometary nuclei most likely are) must gradually separate through the unequal action of gravity on its various parts—through, in short, solar tidal influence. Thenceforward its fragments will revolve independently in parallel orbits, at first as a swarm, finally—when time has been given for the full effects of the lagging of the slower moving particles to develop—as a closed ring. The first condition is still, more or less, that of the November meteors; those of August have already arrived at the second. For this reason, Leverrier pronounced, in 1867, the Perseid to be of older formation than the Leonid system. He even assigned a date at which the introduction of the last-named bodies into their present orbit was probably effected through the influence of Uranus. In 126 A.D. a close approach must have taken place between the planet and the parent comet of the November stars, after which its regular returns to perihelion, and the consequent process of its disintegration, set in. Though not complete, it is already far advanced.

The view that meteorites are the dust of decaying comets was now to be put to a definite test of prediction. Biela’s comet had not been seen since its duplicate return in 1852. Yet it had been carefully watched for with the best telescopes; its path was accurately known; every perturbation it could suffer was scrupulously taken into account. Under these circumstances, its repeated failure to come up to time might fairly be thought to imply a cessation from visible existence. Might it not, however, be possible that it would appear under another form—that a star-shower might have sprung from and would commemorate its dissolution?

An unusually large number of falling stars were seen by Brandes, December 6, 1798. Similar displays were noticed in the years 1830, 1838, and 1847, and the point from which they emanated was shown by Heis at Aix-la-Chapelle to be situated near the bright star γ Andromedæ.[1221] Now this is precisely the direction in which the orbit of Biela’s comet would seem to lie, as it runs down to cut the terrestrial track very near the place of the earth at the above dates. The inference was, then, an easy one, that the meteors were pursuing the same path with the comet; and it was separately arrived at, early in 1867, by

Weiss, D'Arrest, and Galle.[1222] But Biela travels in the opposite direction to Tempel's comet and its attendant "Leonids"; its motion is direct, or from west to east, while theirs is retrograde. Consequently, the motion of its node is in the opposite direction too. In other words, the meeting-place of its orbit with that of the earth retreats (and very rapidly) along the ecliptic instead of advancing. So that if the "Andromedes" stood in the supposed intimate relation to Biela's comet, they might be expected to anticipate the times of their recurrence by as much as a week in half a century. All doubt as to the fact may be said to have been removed by Signor Zezioli's observation of the annual shower in more than usual abundance at Bergamo, November 30, 1867.

The missing comet was next due at perihelion in the year 1872, and the probability was contemplated by both Weiss and Galle of its being replaced by a copious discharge of falling stars. The precise date of the occurrence was not easily determinable, but Galle thought the chances in favour of November 28. The event anticipated the prediction by twenty-four hours. Scarcely had the sun set in Western Europe on November 27, when it became evident that Biela's comet was shedding over us the pulverised products of its disintegration. The meteors came in volleys from the foot of the Chained Lady, their numbers at times baffling the attempt to keep a reckoning. At Moncalieri, about 8 p.m., they constituted (as Father Denza said[1223]) a "real rain of fire." Four observers counted, on an average, four hundred each minute and a half; and not a few fireballs, equalling the moon in diameter, traversed the sky. On the whole, however, the stars of 1872, though about equally numerous, were less brilliant than those of 1866; the phosphorescent tracks marking their passage were comparatively evanescent and their movements sluggish. This is easily understood when we remember that the Andromedes *overtake* the earth, while the Leonids rush to meet it; the velocity of encounter for the first class of bodies being under twelve, for the second above forty-four miles a second. The spectacle was, nevertheless, magnificent. It presented itself successively to various parts of the earth, from Bombay and the Mauritius to New Brunswick and Venezuela, and was most diligently and extensively observed. Here it had well-nigh terminated by midnight.[1224]

It was attended by a slight aurora, and although Tacchini had telegraphed that the state of the sun rendered some show of polar lights probable, it has too often figured as an accompaniment of star-showers to permit the coincidence to rank as fortuitous. Admiral Wrangel was accustomed to describe how, during the prevalence of an aurora on the Siberian coast, the passage of a meteor never failed to extend the luminosity to parts of the sky previously dark;[1225] and an enhancement of electrical disturbance may well be associated with the flittings of such cosmical atoms.

A singular incident connected with the meteors of 1872 has now to be recounted. The late Professor Klinkerfues, who had observed them very completely at Göttingen, was led to believe that not merely the débris strewn along its path, but the comet itself must have been in immediate proximity to the earth during their appearance.[1226] If so, it might be possible, he thought, to descry it as it retreated in the diametrically opposite direction from that in which it had approached. On November 30, accordingly, he telegraphed to Mr. Pogson, the Madras astronomer, "Biela touched earth November 27; search near Theta Centauri"—the "anti-radiant," as it is called, being situated close to that star. Bad weather prohibited observation during thirty-six hours, but when the rain clouds broke on the morning of December 2, there a comet was, just in the indicated position. In appearance it might have passed well enough for one of the Biela twins. It had no tail, but a decided nucleus, and was about 45 seconds across, being thus altogether below the range of naked-eye discernment. It was again observed December 3, when a short tail was perceptible; but overcast skies supervened, and it has never since been seen. Its identity accordingly remains in doubt. It seems tolerably certain, however, that it was *not* the lost comet, which ought to have passed that spot twelve weeks earlier, and was subject to no conceivable disturbance capable of delaying to that extent its revolution. On the other hand, there is the strongest likelihood that it belonged to the same system[1227]—that it was a third fragment, torn from the parent-body of the Andromedes at a period anterior to our first observations of it.

In thirteen years Biela's comet (or its relics) travels nearly twice round its orbit, so that a renewal of the meteoric shower of 1872 was looked for on the same day of the year 1885, the probability being emphasised by an admonitory circular from Dunecht. Astronomers were accordingly on the alert, and were not disappointed. In England, observation was partially impeded by clouds; but at Malta, Palermo, Beyrout, and other southern stations, the scene was most striking. The meteors were both larger and more numerous than in 1872. Their numbers in the densest part of the drift were estimated by Professor Newton at 75,000 per hour, visible from one spot to so large a group of spectators that practically none could be missed. Yet each of these multitudinous little bodies was found by him to travel in a clear cubical space of which the edge measured twenty miles![1228] Thus the dazzling effect of a luminous throng was produced without jostling or overcrowding, by particles, it might almost be said, isolated in the void.

Their aspect was strongly characteristic of the Andromede family of meteors. "They invariably," Mr. Denning wrote,[1229] "traversed short paths with very slow motions, and became extinct in evolved streams of yellowish sparks." The conclusion seemed obvious "that these meteors are formed of very soft materials, which expand while incalescent, and are immediately crumbled and dissipated into exiguous dust."

The Biela meteors of 1885 did not merely gratify astronomers with a fulfilled prediction, but were the means of communicating to them some valuable information. Although their main body was cut through by the moving earth in six hours, and was not more than 100,000 miles across, skirmishers were thrown out to nearly a million miles on either side of the compact central battalions. Members of the system were, on the 26th of November, recorded by Mr. Denning at the hourly rate of about 130; and they did not wholly cease to be visible until December 1. They afforded besides a particularly well-marked example of that diffuseness of radiation previously observed in some less conspicuous displays. Their paths seemed to diverge from an area rather than from a point in the sky. They came so ill to focus that divergences of several degrees were found between the most authentically determined radiants. These incongruities are attributed by Professor Newton to the irregular shape of the meteoroids producing unsymmetrical resistance from the air, and hence causing them to glance from their original direction on entering it. Thus, their luminous tracks did not always represent (even apart from the effects of the earth's attraction) the true prolongation of their course through space.

The Andromedes of 1872 were laggards behind the comet from which they sprang; those of 1885 were its avant-couriers. That wasted and disrupted body was not due at the node until January 26, 1886, sixty days, that is, after the earth's encounter with its meteoric fragments. These are now probably scattered over more than five hundred million miles of its orbits;[1230] yet Professor Newton considers that all must have formed one compact group with Biela at the time of its close approach to Jupiter about the middle of 1841. For otherwise both comet and meteorites could not have experienced, as they seem to have done, the same kind and amount of disturbance. The rapidity of cometary disintegration is thus curiously illustrated.

A short-lived persuasion that the missing heavenly body itself had been recovered, was created by Mr. Edwin Holms's discovery, at London, November 6, 1892, of a tolerably bright, tailless comet, just in a spot which Biela's comet must have traversed in approaching the intersection of its orbit with that of the earth. A hasty calculation by Berberich assigned elements to the newcomer seeming not only to ratify the identity, but to promise a quasi-encounter with the earth on November 21. The only effect of the prediction, however, was to raise a panic among the negroes of the Southern States of America. The comet quietly ignored it, and moved away from instead of towards the appointed meeting-place. Its projection, then, on the night of its discovery, upon a point of the Biela-orbit was by a mere caprice of chance. North America, nevertheless, was visited on November 23 by a genuine Andromede shower. Although the meteors were less numerous than in 1885, Professor Young estimated that 30,000, at the least, of their orange fire-streaks came, during five hours, within the range of view at Princeton.[1231] Brédikhine estimated the width of the space containing them at about 2,700,000 miles.[1232] The anticipation of their due time by four days implied—if they were a prolongation of the main Biela group, the nucleus of which passed the spot of encounter five months previously—a recession of the node since 1885 by no less than three degrees. Unless, indeed, Mr. Denning were right in supposing the display to have proceeded from "an associated branch of the main swarm through which we passed in 1872 and 1885."[1233] The existence of separated detachments of Biela meteors, due to disturbing planetary action, was contemplated as highly probable by Schiaparelli.[1234] Such may have been the belated flights met with in 1830, 1838, 1841, and 1847, and such the advance flight plunged through in 1892. A shower looked for November 23, 1899, did not fall, and no further display from this quarter is probable until November 17, 1905, although one is possible a year earlier.[1235]

The Leonids, through the adverse influence of Jupiter and Saturn, inflicted upon multitudes of eager watchers a still more poignant disappointment. A dense part of the swarm, having nearly completed a revolution since 1866, should, travelling normally, have met the earth November 15, 1899; in point of fact, it swerved sunward, and the millions of meteorites which would otherwise have been sacrificed for the illumination of our skies escaped a fiery doom. The contingency had been forecast in the able calculations of Dr. Johnstone Stoney and Dr. A. M. W. Downing,[1236] superintendent of the Nautical Almanac Office; but the verification scarcely compensated the failure. Nor was the situation retrieved in the following years. Only ragged fringes of the great tempest-cloud here and there touched our globe. As the same investigators warned us to expect, the course of the meteorites had been not only rendered sinuous by perturbation, but also broken and irregular. We can no longer count upon the Leonids. Their glory, for scenic purposes, is departed. The comet associated with them also evaded observation. Although it doubtless kept its tryst with the sun in the spring of 1899, the attendant circumstances were too unfavourable to allow it to be seen from the earth.[1237] By an almost fantastic coincidence, nevertheless, a faint comet was photographed, November 14, 1898,[1238] by Dr. Chase, of the Yale College Observatory, close to the Leonid radiant, whither a "meteorograph" was directed with a view to recording trails left by precursors of the main Leonid body. A promising start, too, was made on the same occasion with meteoric researches from sensitive plates.[1239] Indeed, Schaeberle and Colton[1240] had already, in 1896, determined the height of a Leonid by means of photographs taken at stations on different ridges of Mount Hamilton; and Professor Pickering has prosecuted similar work at Harvard, with encouraging results. Everything in this branch of science depends upon how far they can be carried. Without the meteorograph, rigid accuracy in the observation of shooting stars is unattainable, and rigid accuracy is the *sine quâ non* for obtaining exact knowledge.

Biela does not offer the only example of cometary disruption. Setting aside the unauthentic reports of early chroniclers, we meet the "double comet" discovered by Liais at Olinda (Brazil), February 27, 1860, of which the division appeared recent, and about to be carried farther.[1241] But a division once established, separation must continually progress. The periodic times of the fragments will never be identical; one must drop a little behind the other at each revolution, until at length they come to travel in remote parts of nearly the same orbit. Thus the comet predicted by Klinkerfues and discovered by Pogson had already lagged to the extent of twelve weeks, and we shall meet instances farther on where the retardation is counted, not by weeks, but by years. Here original identity emerges only from calculation and comparison of orbits.

Comets, then, die, as Kepler wrote long ago, *sicut bombyces filo fundendo*. This certainty, anticipated by Kirkwood in 1861, we have at least acquired from the discovery of their generative connection with meteors. Nay, their actual materials become, in smaller or larger proportions, incorporated with our globe. It is not, indeed, universally admitted that the ponderous masses of which, according to Daubrée's estimate,[1242] at least 600 fall annually from space upon the earth, ever formed part of the bodies known to us as comets. Some follow Tschermak in attributing to aerolites a totally different origin from that of periodical shooting-stars. That no clear line of demarcation can be drawn is no valid reason for asserting that no real distinction exists; and it is certainly remarkable that a meteoric fusillade may be kept up for hours without a single solid projectile reaching its destination. It would seem as if the celestial army had been supplied with blank cartridges. Yet, since a few detonating meteors have been found to proceed from ascertained radiants of shooting-stars, it is difficult to suppose that any generic difference separates them.

Their assimilation is further urged—though not with any demonstrative force—by two instances, the only two on record, of the tangible descent of an aerolite during the progress of a star-shower. On April 4, 1095, the Saxon Chronicle informs us that stars fell "so thickly that no man could count them," and adds that one of them having struck the ground in France, a bystander "cast water upon it, which was raised in steam with a great noise of boiling."[1243] And again, on November 27, 1885, while the skirts of the Andromede-tempest were trailing over Mexico, "a ball of fire" was precipitated from the sky at Mazapil, within view of a ranchman.[1244] Scientific examination proved it to be a "siderite," or mass of "nickel-iron"; its weight exceeded eight pounds, and it contained many nodules of graphite. We are not, however, authorised by the circumstances of its arrival to regard the Mazapil fragment of cosmic metal as a specimen torn from Biela's comet. In this, as in the preceding case, the coincidence of the fall with the shower may have been purely casual, since no hint is given of any sort of agreement between the tracks followed by the sample provided for curious study, and the swarming meteors consumed in the upper air.

Professor Newton's inquiries into the tracks pursued by meteorites previous to their collisions with the earth tend to distinguish them, at least specifically, from shooting-stars. He found that nearly all had been travelling with a direct movement in orbits the perihelia of which lay in the outer half of the space separating the earth from the sun.[1245] Shooting-stars, on the contrary, are entirely exempt from such limitations. The Yale Professor concluded "that the larger meteorites moving in our solar system are allied much more closely with the group of comets of short period than with the comets whose orbits are nearly parabolic." They would thus seem to be more at home than might have been expected amid the planetary family. Father Carbonelle has, moreover, shown[1246] that meteorites, if explosion-products of the earth or moon, should, with rare exceptions, follow just the kind of paths assigned to them, from data of observation, by Professor Newton. Yet it is altogether improbable that projectiles from terrestrial volcanoes should, at any geological epoch, have received impulses powerful enough to enable them, not only to surmount the earth's gravity, but to penetrate its atmosphere.

A striking—indeed, an almost startling—peculiarity, on the other hand, divides from their congeners a class of meteors identified by Mr. Denning during ten years' patient watching of such phenomena at Bristol.[1247] These are described as "meteors with stationary radiants," since for months together they seem to come from the same fixed points in the sky. Now this implies quite a portentous velocity. The direction of meteor-radiants is affected by a kind of *aberration*, analogous to the aberration of light. It results from a composition of terrestrial with meteoric motion. Hence, unless that of the earth in its orbit be by comparison insignificant, the visual line of encounter must shift, if not perceptibly from day to day, at any rate conspicuously from month to month. The fixity, then, of many systems observed by Mr. Denning seems to demand the admission that their members travel so fast as to throw the earth's movement completely out of the account. The required velocity would be, by Mr. Ranyard's calculation, at least 880 miles a second.[1248] But the aspect of the meteors justifies no such extravagant assumption. Their seeming swiftness is very various, and—what is highly significant—it is notably less when they pursue than when they meet the earth. Yet the "incredible and unaccountable"[1249] fact of the existence of these "long radiants," although doubted by Tisserand[1250] because of its theoretical refractoriness, must apparently be admitted. The first plausible explanation of them was offered by Professor Turner in 1899.[1251] They represent, in his view, the cumulative effects of the earth's attraction. The validity of his reasoning is, however, denied by M. Brédikhine,[1252] who prefers to regard them as a congeries of separate streams. The enigma they present has evidently not yet received its definitive solution.

The Perseids afford, on the contrary, a remarkable instance of a "shifting radiant." Mr. Denning's observations of these yellowish, leisurely meteors extend over nearly six weeks, from July 8 to August 16; the point of radiation meantime progressing no less than 57° in right ascension. Doubts as to their common origin were hence freely expressed, especially by Mr. Monck of Dublin.[1253] But the late Dr. Kleiber[1254] showed, by strict geometrical reasoning, that the forty-nine radiants successively determined for the shower were all, in fact, comprised within one narrowly limited region of space. In other words, the application of the proper correction for the terrestrial movement, and the effects of attraction by which each individual shooting-star is compelled to describe a hyperbola round the earth's centre, reduces the extended line of radiants to a compact group, with the cometary radiant for its central point; the cometary radiant being the spot in the sky met by a tangent to the orbit of the Perseid comet of 1862 at its intersection with the orbit of the earth. The reality of the connection between the comet and the meteors could scarcely be more clearly proved; while the vast dimensions of the stream into which the latter are found to be diffused cannot but excite astonishment not unmixed with perplexity.

The first successful application of the spectroscope to comets was by Donati in 1864.[1255]

A comet discovered by Tempel, July 4, brightened until it appeared like a star somewhat below the second magnitude, with a feeble tail 30° in length. It was remarkable as having, on August 7, almost totally eclipsed a small star—a very rare occurrence.[1256] On August 5 Donati admitted its light through his train of prisms, and found it, thus analysed, to consist of three bright bands—yellow, green, and blue—separated by wider dark intervals. This implied a good deal. Comets had previously been considered, as we have seen, to shine mainly, if not wholly, by reflected sunlight. They were now perceived to be self-luminous, and to be formed, to a large extent, of glowing gas. The next step was to determine what *kind* of gas it was that was thus glowing in them; and this was taken by Sir William Huggins in 1868.[1257]

A comet of subordinate brilliancy, known as comet 1868 ii., or sometimes as Winnecke's, was the subject of his experiment. On comparing its spectrum with that of an olefiant-gas "vacuum tube" rendered luminous by electricity, he found the agreement exact. It has since been abundantly confirmed. All the eighteen comets tested by light analysis, between 1868 and 1880, showed the typical hydro-carbon spectrum[1258] common to the whole group of those compounds, but probably due immediately to the presence of acetylene. Some minor deviations from the laboratory pattern, in the shifting of the maxima of light from the edge towards the middle of the yellow and blue bands, have been experimentally reproduced by Vogel and Hasselberg in tubes containing a mixture of carbonic oxide with olefiant gas.[1259] Their illumination by disruptive electric discharges was, however, a condition *sine quâ non* for the exhibition of the cometary type of spectrum. When a continuous current was

PLATE II.

Great Comet. Photographed, May 5, 1901, with the thirteen-inch Astrographic Refractor of the Royal Observatory, Cape of Good Hope.

Great Comet.
Photographed, May 5, 1901, with the thirteen-inch Astrographic Refractor of the Royal Observatory, Cape of Good Hope.

employed, the carbonic oxide bands asserted themselves to the exclusion of the hydro-carbons. The distinction has great significance as regards the nature of comets. Of particular interest in this connection is the circumstance that carbonic oxide is one of the gases evolved by meteoric stones and irons under stress of heat.[1260] For it must apparently have formed part of an aeriform mass in which they were immersed at an earlier stage of their history.

In a few exceptional comets the usual carbon-bands have been missed. Two such were observed by Sir William Huggins in 1866 and 1867 respectively.[1261] In each a green ray, approximating in position to the fundamental nebular line, crossed an otherwise unbroken spectrum. And Holmes's comet of 1892 displayed only a faint prismatic band devoid of any characteristic feature.[1262] Now these three might well be set down as partially effete bodies; but a brilliant comet, visible in southern latitudes in April and May, 1901, so far resembled them in the quality of its light as to give a spectrum mainly, if not purely, continuous. This, accordingly, is no symptom of decay.

The earliest comet of first-class lustre to present itself for spectroscopic examination was that discovered by Coggia at Marseilles, April 17, 1874. Invisible to the naked eye till June, it blazed out in July a splendid ornament of our northern skies, with a just perceptibly curved tail, reaching more than half way from the horizon to the zenith, and a nucleus surpassing in brilliancy the brightest stars in the Swan. Brédikhine, Vogel, and Huggins[1263] were unanimous in pronouncing its spectrum to be that of marsh or olefiant gas. Father Secchi, in the clear sky of Rome, was able to push the identification even closer than had heretofore been done. The *complete* hydro-carbon spectrum consists of five zones of variously coloured light. Three of these only—the three central ones—had till then been obtained from comets; owing, it was supposed, to their temperature not being high enough to develop the others. The light of Coggia's comet, however, was found to contain all five, traces of the violet band emerging June 4, of the red, July 2.[1264] Presumably, all five would show universally in cometary spectra, were the dispersed rays strong enough to enable them to be seen.

The gaseous surroundings of comets are, then, largely made up of a compound of hydrogen with carbon. Other materials are also present; but the hydro-carbon element is probably unfailing and predominant. Its luminosity is, there is little doubt, an effect of electrical excitement. Zöllner showed in 1872[1265] that, owing to evaporation and other changes produced by rapid approach to the sun, electrical processes of considerable intensity must take place in comets; and that their original light is immediately connected with these, and depends upon solar radiation, rather through its direct or indirect electrifying effects, than through its more obvious thermal power, may be considered a truth permanently acquired to science.[1266] They are not, it thus seems, bodies incandescent through heat, but glowing by electricity; and this is compatible, under certain circumstances, with a relatively low temperature.

The gaseous spectrum of comets is accompanied, in varying degrees, by a continuous spectrum. This is usually derived most strongly from the nucleus, but extends, more or less, to the nebulous appendages. In part, it is certainly due to reflected sunlight; in part, most likely, to the ignition of minute solid particles.

FOOTNOTES:

[1188] *Month. Not.*, vol. xix., p. 27.

[1189] *Mém. de l'Ac. Imp.*, t. ii., 1859, p. 46.

[1190] *Harvard Annals*, vol. iii., p. 368.

[1191] *Ibid.*, p. 371.

[1192] *Month. Not.*, vol. xxii., p. 306.

[1193] Stothard in *Ibid.*, vol. xxi., p. 243.

[1194] *Intell. Observer*, vol. i., p. 65.

[1195] *Comptes Rendus*, t. lxi., p. 953.

[1196] *Smiths. Report*, 1881 (Holden); *Nature*, vol. xxv., p. 94; *Observatory*, vol. xxi., p. 378 (W. T. Lynn).

[1197] *Ueber den Ursprung der von Pallas gefundenen Eisenmassen*, p. 24.

[1198] Arago, *Annuaire*, 1836, p. 294.

[1199] Humboldt had noticed the emanation of the shooting stars of 1799 from a single point, or "radiant," as Greg long afterwards termed it; but no reasoning was founded on the observation.

[1200] *Am. Journ. of Sc.*, vol. xxvi., p. 132.

[1201] *Annuaire*, 1836, p. 297.

[1202] *Ann. de l'Observ.*, Bruxelles, 1839, p. 248.

[1203] *Ibid.*, 1837, p. 272.

[1204] *Astr. Nach.*, Nos. 385, 390.

[1205] *Am. Jour. of Sc.*, vol. xxxviii. (2nd ser.), p. 377.

[1206] *Ibid.*, vol. xxxviii., p. 61.

[1207] *Month. Not.*, vol. xxvii., p. 247.

[1208] *Am. Jour. of Sc.*, vol. xliii. (2nd ser.), p. 87.

[1209] Grant, *Month. Not.*, vol. xxvii., p. 29.

[1210] P. Smyth, *Ibid.*, p. 256.

[1211] Hind, *Ibid.*, p. 49.

[1212] Reproduced in *Les Mondes*, t. xiii.

[1213] *Comptes Rendus*, t. lxiv., p. 96.

[1214] *Astr. Nach.*, No. 1,626.

[1215] *Ibid.*, No. 1,632.

[1216] *Month. Not.*, vol. xxxviii., p. 369.

[1217] Schiaparelli, *Le Stelle Cadenti*, p. 54.

[1218] *Ueber Feuer-Meteore*, p. 406.

[1219] *Astr. Nach.*, No. 347 (Mädler); see also Boguslawski, *Die Kometen*, p. 98. 1857.

[1220] *Nature*, vol. vi., p. 148.

[1221] A. S. Herschel, *Month. Not.*, vol. xxxii., p. 355.

[1222] *Astr. Nach.*, Nos. 1,632, 1,633, 1,635.

[1223] *Nature*, vol. vii., p. 122.

[1224] A. S. Herschel, *Report Brit. Ass.*, 1873, p. 390.

[1225] Humboldt, *Cosmos*, vol. i., p. 114 (Otté‘s trans.).

[1226] *Month. Not.*, vol. xxxiii., p. 128.

[1227] Even this was denied by Bruhns, *Astr. Nach.*, No. 2,054.

[1228] *Am. Jour.*, vol. xxxi., p. 425.

[1229] *Month. Not.*, vol. xlvi., p. 69.

[1230] In Schiaparelli’s opinion, centuries must have elapsed while the observed amount of scattering was being produced. *Le Stelle Cadenti*, 1886, p. 112.

[1231] *Astr. and Astroph.*, vol. xi., p. 943.

[1232] *Bull. de l’Acad. St. Petersbourg*, t. xxxv., p. 598. 1894.

[1233] *Observatory*, vol. xvi., p. 55.

[1234] *Le Stelle Cadenti*, p. 133; *Rendiconti dell’ Istituto Lombardo*, t. iii., ser. ii., p. 23.

[1235] Denning, *Memoirs Roy. Astr. Soc.*, vol. liii., p. 214; Abelmann, *Astr. Nach.*, No. 3,516.

[1236] *Proc. Roy. Soc.*, March 2, 1899; *Nature*, November 9, 1899.

[1237] Berberich, *Astr. Nach.*, No. 3,526.

[1238] Elkin, *Astroph. Jour.*, vol. ix., p. 22.

[1239] Elkin, *Astroph. Jour.*, vol. x., p. 24.

[1240] *Pop. Astr.*, September, 1897, p. 232.

[1241] *Month. Not.*, vol. xx., p. 336.

[1242] *Revue des deux Mondes*, December 15, 1885, p. 889.

[1243] Palgrave, *Phil. Trans.*, vol. cxxv., p. 175.

[1244] W. E. Hidden, *Century Mag.*, vol. xxxiv., p. 534.

[1245] *Amer. Jour. of Science*, vol. xxxvi., p. i., 1888.

[1246] *Revue des Questions Scientifiques*, January, 1899, p. 194; Tisserand, *Bull. Astr.*, t. viii., p. 460.

[1247] *Month. Not.*, vol. xlv., p. 93.

[1248] *Observatory*, vol. viii., p. 4.

[1249] Denning, *Month. Not.*, vol. xxxviii., p. 114.

[1250] *Comptes Rendus*, t. cix., p. 344.

[1251] *Month. Not.*, vol. lix., p. 140.

[1252] *Bull. de l’Acad. St. Petersb.*, t. xii., p. 95.

[1253] *Publ. Astr. Pac. Soc.*, vol. iii., p. 114.

[1254] *Month. Not.*, vol. lii., p. 341.

[1255] *Astr. Nach.*, No. 1,488.

[1256] *Annuaire*, Paris, 1883, p. 185.

[1257] *Phil. Trans.*, vol. clviii., p. 556.

[1258] Hasselberg, *Mém. de l'Ac. Imp. de St. Pétersbourg*, t. xxviii. (7th ser.), No. 2, p. 66.

[1259] Scheiner, *Die Spectralanalyse der Gestirne*, p. 234. Kayser (*Astr. and Astroph.*, vol. xiii., p. 368) refers the anomalies of the carbon-spectrum in comets wholly to instrumental sources.

[1260] Dewar, *Proc. Roy. Inst.*, vol. xi., p. 541.

[1261] *Proc. R. Soc.*, vol. xv., p. 5; *Month. Not.*, vol. xxvii., p. 288.

[1262] Keeler, *Astr. and Astrophysics*, vol. xi., p. 929; Vogel, *Astr. Nach.*, No. 3,142.

[1263] *Proc. Roy. Soc.*, vol. xxiii., p. 154.

[1264] Hasselberg, *loc. cit.*, p. 58.

[1265] *Ueber die Natur der Cometen*, p. 112.

[1266] Hasselberg, *loc. cit.*, p. 38.

CHAPTER XI

RECENT COMETS (*continued*)

The mystery of comets' tails had been to some extent penetrated; so far, at least, that, by making certain assumptions strongly recommended by the facts of the case, their forms can be, with very approximate precision, calculated beforehand. We have, then, the assurance that these extraordinary appendages are composed of no ethereal or supersensual stuff, but of matter such as we know it, and subject to the ordinary laws of motion, though in a state of extreme tenuity.

Olbers, as already stated, originated in 1812 the view that the tails of comets are made up of particles subject to a force of electrical repulsion proceeding from the sun. It was developed and enforced by Bessel's discussion of the appearances presented by Halley's comet in 1835. He, moreover, provided a formula for computing the movement of a particle under the influence of a repulsive force of any given intensity, and thus laid firmly the foundation of a mathematical theory of cometary emanations. Professor W. A. Norton, of Yale College, considerably improved this by inquiries begun in 1844, and resumed on the apparition of Donati's comet; and Dr. C. F. Pape at Altona[1267] gave numerical values for the impulses outward from the sun, which must have actuated the materials respectively of the curved and straight tails adorning the same beautiful and surprising object.

The *physical* theory of repulsion, however, was, it might be said, still in the air. Nor did it even begin to assume consistency until Zöllner took it in hand in 1871.[1268] It is perfectly well ascertained that the energy of the push or pull produced by electricity depends (other things being the same) upon the *surface* of the body acted on; that of gravity upon its *mass*. The efficacy of solar electrical repulsion relatively to solar gravitational attraction grows, consequently, as the size of the particle diminishes. Make this small enough, and it will virtually cease to gravitate, and will unconditionally obey the impulse to recession.

This principle Zöllner was the first to realise in its application to comets. It gives the key to their constitution. Admitting that the sun and they are similarly electrified, their more substantially aggregated parts will still follow the solicitations of his gravity, while the finely divided particles escaping from them will, simply by reason of their minuteness, fall under the sway of his repellent electric power. They will, in other words, form "tails." Nor is any extravagant assumption called for as to the intensity of the electrical charge concerned in producing these effects. Zöllner, in fact, showed[1269] that it need not be higher than that attributed by the best authorities to the terrestrial surface.

Forty years have elapsed since M. Brédikhine, director successively of the Moscow and of the Pulkowa Observatories, turned his attention to these curious phenomena. His persistent inquiries on the subject, however, date from the appearance of Coggia's comet in 1874. On computing the value of the repulsive force exerted in the formation of its tail, and comparing it with values of the same force arrived at by him in 1862 for some other conspicuous comets, it struck him that the numbers representing them fell into three well-defined classes. "I suspect," he wrote in 1877, "that comets are divisible into groups, for each of which the repulsive force is perhaps the same."[1270] This idea was confirmed on fuller investigation. In 1882 the appendages of thirty-six well-observed comets had been reconstructed theoretically, without a single exception being met with to the rule of the three types. A further study of forty comets led, in 1885, only to a modification of the numerical results previously arrived at.

In the first of these, the repellent energy of the sun is fourteen times stronger than his attractive energy;[1271] the particles forming the enormously long straight rays projected outward from this kind of comet leave the nucleus with a mean velocity of just seven kilometres per second, which, becoming constantly accelerated, carries them in a few days to the limit of visibility. The great comets of 1811, 1843, and 1861, that of 1744 (so far as its principal tail was concerned), and Halley's comet at its various apparitions, belonged to this class. Less narrow limits were assigned to the values of the repulsive force employed to produce the second type. For the axis of the tail, it exceeds by one-tenth (= 1·1) the power of solar gravity; for the anterior edge, it is more than twice (2·2), for the posterior only half as strong. The corresponding initial velocity (for the axis) is 1,500 metres a second, and the resulting appendage a scimitar-like or plumy tail, such as Donati's and Coggia's comets furnished splendid examples of. Tails of the third type are constructed with forces of repulsion from the sun ranging from one-tenth to three-tenths that of his gravity, producing an accelerated movement of attenuated matter from the nucleus, beginning at the leisurely rate of 300 to 600 metres a second. They are short, strongly bent, brush-like emanations, and in bright comets seem to be only found in combination with tails of the higher classes. Multiple tails, indeed—that is, tails of different types emitted simultaneously by one comet—are perceived, as experience advances and observation becomes closer, to be rather the rule than the exception.[1272]

Now what is the meaning of these three types? Is any translation of them into physical fact possible? To this question Brédikhine supplied, in 1879, a plausible answer.[1273] It was already a current surmise that multiple tails are composed of different kinds of matter, differently acted on by the sun. Both Olbers and Bessel had suggested this explanation of the straight and curved emanations from the comet of 1807; Norton had applied it to the faint light tracks proceeding from that of Donati;[1274] Winnecke to the varying deviations of its more brilliant plumage. Brédikhine defined and ratified the conjecture. He undertook to determine (provisionally as yet) the several kinds of matter appropriated severally to the three classes of tails. These he found to be hydrogen for the first, hydro-carbons for the second, and iron for the third. The ground of this apportionment is that the atomic weights of these substances bear to each other the same inverse proportion as the repulsive forces employed in producing the appendages they are supposed to form; and Zöllner had pointed out in 1875 that the "heliofugal" power by which comets' tails are developed would, in fact, be effective just in that ratio.[1275] Hydrogen, as the lightest known element—that is, the least under the influence of gravity—was naturally selected as that which yielded most readily to the counter-persuasions of electricity. Hydro-carbons had been shown by the spectroscope to be present in comets, and were fitted by their specific weight, as compared with that of hydrogen, to form tails of the second type; while the atoms of iron were just heavy enough to compose those of the third, and, from the plentifulness of their presence in meteorites, might be presumed to enter, in no inconsiderable proportion, into the mass of comets. These three substances, however, were by no means supposed to be the sole constituents of the appendages in question. On the contrary, the great breadth of what, for the present, were taken to be characteristically "iron" tails was attributed to the presence of many kinds of matter of high and slightly different specific weights;[1276] while the expanded plume of Donati was shown to be, in reality, a whole system of tails, made up of many substances, each spreading into a separate hollow cone, more or less deviating from, and partially superposed upon the others.

Yet these felicities of explanation must not make us forget that the chemical composition attributed to the first type of cometary trains has, so far, received no countenance from the spectroscope. The emission lines of free, incandescent hydrogen have never been derived from any part of these bodies. Dissentient opinions, accordingly, were expressed as to the cause of their structural peculiarities. Ranyard,[1277] Zenker, and others advocated the agency of heat repulsion in producing them; Kiaer somewhat obscurely explains them through the evolution of gases by colliding particles;[1278] Herz of Vienna concludes tails to be mere illusory appendages produced by electrical discharges through the rare medium assumed to fill space.[1279] But Hirn[1280] conclusively showed that no such medium could possibly exist without promptly bringing ruin upon our "dædal earth" and its revolving companions.

On the whole, modern researches tend to render superfluous the chemical diversities postulated by Brédikhine. Electricity alone seems competent to produce the varieties of cometary emanation they were designed to account for. The distinction of types rests on a solid basis of fact, but probably depends upon differences rather in the mode of action than in the kind of substance acted upon. Suggestive sketches of electrical and "light-pressure" theories of comets have been published respectively by Mr. Fessenden of Alleghany,[1281] and by M. Arrhenius at Stockholm.[1282] Although evidently of a tentative character, they possess great interest.

Brédikhine's hypothesis was promptly and profusely illustrated. Within three years of its promulgation, five bright comets made their appearance, each presenting some distinctive peculiarity by which knowledge of these curious objects was materially helped forward.

The first of these is remembered as the "Great Southern Comet." It was never visible in these latitudes, but made a short though stately progress through southern skies. Its earliest detection was at Cordoba on the last evening of January, 1880; and it was seen on February 1, as a luminous streak, extending just after sunset from the south-west horizon towards the pole, in New South Wales, at Monte Video, and the Cape of Good Hope. The head was lost in the solar rays until February 4, when Dr. Gould, then director of the National Observatory of the Argentine Republic at Cordoba, caught a glimpse of it very low in the west; and on the following evening, Mr. Eddie, at Graham's Town, discovered a faint nucleus, of a straw-coloured tinge, about the size of the annular nebula in Lyra. Its condensation, however, was very imperfect, and the whole apparition showed an exceedingly filmy texture. The tail was enormously long. On February 5 it extended—large perspective retrenchment notwithstanding—over an arc of 50°; but its brightness nowhere exceeded that of the Milky Way in Taurus. There was little curvature perceptible; the edges of the appendage ran parallel, forming a nebulous causeway from star to star; and the comparison to an auroral beam was appropriately used. The aspect of the famous comet of 1843 was forcibly recalled to the memory of Mr. Janisch, Governor of St. Helena; and the resemblance proved not merely superficial. But the comet of 1880 was less brilliant, and even more evanescent. After only eight days of visibility, it had faded so much as no longer to strike, though still discoverable by the unaided eye; and on February 20 it was invisible with the great Cordoba equatoreal pointed to its known place.

But the most astonishing circumstance connected with this body is the identity of its path with that of its predecessor in 1843. This is undeniable. Dr. Gould,[1283] Mr. Hind, and Dr. Copeland,[1284] each computed a separate set of elements from the first rough observations, and each was struck with an agreement between the two orbits so close as to render them virtually indistinguishable. "Can it be possible," Mr. Hind wrote to Sir George Airy, "that there is such a comet in the system, almost grazing the sun's surface in perihelion, and revolving in less than thirty-seven years. I confess I feel a difficulty in admitting it, notwithstanding the above extraordinary resemblance of orbits."[1285]

Mr. Hind's difficulty was shared by other astronomers. It would, indeed, be a violation of common-sense to suppose that a celestial visitant so striking in appearance had been for centuries back an unnoticed frequenter of our skies. Various expedients, accordingly, were resorted to for getting rid of the anomaly. The most promising at first sight was that of the resisting medium. It was hard to believe that a body, largely vaporous, shooting past the sun at a distance of less than a hundred thousand miles from his surface, should have escaped powerful retardation. It must have passed through the very midst of the corona. It might easily have had an actual encounter with a prominence. Escape from such proximity might, indeed, very well have been judged beforehand to be impossible. Even admitting no other kind of opposition than that dubiously supposed to have affected Encke's comet, the result in shortening the period ought to be of the most marked kind. It was proved by Oppolzer[1286] that if the comet of 1843 had entered our system from stellar space with parabolic velocity it would, by the action of a medium such as Encke postulated (varying in density inversely as the square of the distance from the sun), have been brought down, by its first perihelion passage, to elliptic movement in a period of twenty-four years, with such rapid diminution that its next return would be in about ten. But such restricted observations as were available on either occasion of its visibility gave no sign of such a rapid progress towards engulfment.

Another form of the theory was advocated by Klinkerfues.[1287] He supposed that four returns of the same body had been witnessed within historical memory—the first in 371 B.C., the next in 1668, besides those of 1843 and 1880; an original period of 2,039 years being successively reduced by the withdrawal at each perihelion passage of 1/1320 of the velocity acquired by falling from the far extremity of its orbit towards the sun, to 175 and 37 years. A continuance of the process would bring the comet of 1880 back in 1897.

Unfortunately, the earliest of these apparitions cannot be identified with the recent ones unless by doing violence to the plain meaning of Aristotle's words in describing it. He states that the comet was first seen "during the frosts and in the clear skies of winter," setting due west nearly at the same time as the sun.[1288] This implies some considerable north latitude. But the objects lately observed had practically *no* north latitude. They accomplished their entire course *above* the ecliptic in two hours and a quarter, during which space they were barely separated a hand's-breadth (one might say) from the sun's surface. For the purposes of the desired assimilation, Aristotle's comet should have appeared in March. It is not credible, however, that even a native of Thrace should have termed March "winter."

With the comet of 1668 the case seemed more dubious. The circumstances of its appearance are barely reconcilable with the identity attributed to it, although too vaguely known to render certainty one way or the other attainable. It might however, be expected that recent observations would at least decide the questions whether the comet of 1843 could have returned in less than thirty-seven, and whether the comet of 1880 was to be looked for at the end of 17-1/2 years. But the truth is that both these objects were observed over so small an arc—8° and 3° respectively—that their periods remained virtually undetermined. For while the shape and position of their orbits could be and were fixed with a very close approach to accuracy, the length of those orbits might vary enormously without any very sensible difference being produced in the small part of the curves traced out near the sun. Dr. Wilhelm Meyer, however, arrived, by an elaborate discussion, at a period of thirty-seven years for the comet of 1880,[1289] while the observations of 1843 were admittedly best fitted by Hubbard's ellipse of 533 years; but these Dr. Meyer supposed to be affected by some constant source of error, such as would be produced by a mistaken estimate of the position of the comet's centre of gravity. He inferred finally that, in spite of previous non-appearances, the two comets represented a single regular denizen of our system, returning once in thirty-seven years along an orbit of such extreme eccentricity that its movement might be described as one of precipitation towards and rapid escape from the sun, rather than of sedate circulation round it.

The *geometrical* test of identity has hitherto been the only one which it was possible to apply to comets, and in the case before us it may fairly be said to have broken down. We may, then, tentatively, and with much hesitation, try a *physical* test, though scarcely yet, properly speaking, available. We have seen that the comets of 1843 and 1880 were strikingly alike in general appearance, though the absence of a formed nucleus in the latter, and its inferior brilliancy, detracted from the convincing effect of the resemblance. Nor was it maintained when tried by exact methods of inquiry. M. Brédikhine found that the gigantic ray emitted in 1843 belonged to his type No. 1; that of 1880 to type No. 2. [1290] The particles forming the one were actuated by a repulsive force ten times as powerful as those forming the other. It is true that a second noticeably curved tail was seen in Chili, March 1, and at Madras, March 11, 1843; and the conjecture was accordingly hazarded that the materials composing on that occasion the principal appendage having become exhausted, those of the secondary one remained predominant, and reappeared alone in the "hydro-carbon" train of 1880. But the one known instance in point is against such a supposition. Halley's comet, the only *great* comet of which the returns have been securely authenticated and carefully observed, has preserved its "type" unchanged through many successive revolutions. The dilemma presented to astronomers by the Great Southern Comet of 1880 was unexpectedly renewed in the following year.

On the 22nd of May, 1881, Mr. John Tebbutt of Windsor, New South Wales, scanning the western sky, discerned a hazy-looking object which he felt sure was a strange one. A marine telescope at once resolved it into two small stars and a comet, the latter of which quickly attracted the keen attention of astronomers; for Dr. Gould, computing its orbit from his first observations at Cordoba, found it to agree so closely with that arrived at by Bessel for the comet of 1807 that he telegraphed to Europe, June 1, announcing the unexpected return of that body. So unexpected that theoretically it was not possible before the year 3346; and Bessel's investigation was one which inspired and eminently deserved confidence. Here, then, once more the perplexing choice had to be made between a premature and unaccountable reappearance and the admission of a plurality of comets moving nearly in the same path. But in this case facts proved decisive.

Tebbutt's comet passed the sun, June 16, at a distance of sixty-eight millions of miles, and became visible in Europe six days later. It was, in the opinion of some, the finest object of the kind since 1861. In traversing the constellation Auriga on its *début* in these latitudes, it outshone Capella. On June 24 and some subsequent nights, it was unmatched in brilliancy by any star in the heavens. In the telescope, the "two interlacing arcs of light" which had adorned the head of Coggia's comet were reproduced; while a curious *dorsal spine* of strong illumination formed the axis of the tail, which extended in clear skies over an arc of 20°. It belonged to the same "type" as Donati's great plume; the particles composing it being driven *from* the sun by a force twice as powerful as that urging them *towards* it.[1291] But the appendage was, for a few nights, and by two observers perceived to be double. Tempel, on June 27, and Lewis Boss, at Albany (N.Y.), June 26 and 28, saw a long straight ray corresponding to a far higher rate of emission than the curved train, and shown by Brédikhine to be a member of the (so-called) hydrogen class. It had vanished by July 1, but made a temporary reappearance July 22.[1292]

The appendages of this comet were of remarkable transparency. Small stars shone wholly undimmed across the tail, and a very nearly central transit of the head over one of the seventh magnitude on the night of June 29, produced—if any change—an increase of brilliancy in the object of this spontaneous experiment.[1293] Dr. Meyer, indeed, at the Geneva Observatory, detected apparent signs of refractive action upon rays thus transmitted;[1294] but his observations remain isolated, and were presumably illusory.

The track pursued by this comet gave peculiar advantages for its observation. Ascending from Auriga through Camelopardus, it stood, July 19, on a line between the Pointers and the Pole, within 8° of the latter, and thus remained for a lengthened period constantly above the horizon of northern observers. Its brightness, too, was no transient blaze, but had a lasting quality which enabled it to be kept steadily in view during nearly nine months. Visible to the naked eye until the end of August, the last telescopic observation of it was made February 14, 1882, when its distance from the earth considerably exceeded 300 million miles. Under these circumstances, the knowledge acquired of its orbit was of more than usual accuracy, and showed conclusively that the comet was not a simple return of Bessel's; for this would involve a period of seventy-four years, whereas Tebbutt's comet cannot revisit the sun until after the lapse of two and a half millenniums.[1295] Nevertheless, the twin bodies move so nearly in the same path that an original connection of some kind is obvious; and the recent example of Biela readily suggested a conjecture as to what the nature of that connection might have been. The comets of 1807 and 1881 are, then, regarded with much probability as fragments of a primitive disrupted body, one following in the wake of the other at an interval of seventy-four years.

Imperfect photographs were taken of Donati's comet both in England and America;[1296] but Tebbutt's comet was the first to which the process was satisfactorily applied. The difficulties to be overcome were very great. The chemical intensity of cometary light is, to begin with, extraordinarily small. Janssen estimated it at 1/300000 of moonlight.[1297] Hence, if the ordinary process by which lunar photographs are taken had been applied to the comet of 1881, an exposure of at least *three days* would have been required in order to get an impression of the head with about a tenth part of the tail. But by that time a new method of vastly increased sensitiveness had been rendered available, by which dry gelatine-plates were substituted for the wet collodion-plates hitherto in use; and this improvement alone reduced the necessary time of exposure to two hours. It was brought down to half an hour by Janssen's employment of a reflector specially adapted to give an image illuminated eight or ten times as strongly as that produced in the focus of an ordinary telescope.[1298]

The photographic feebleness of cometary rays was not the only obstacle in the way of success. The proper motion of these bodies is so rapid as to render the usual devices for keeping a heavenly body steadily in view quite inapplicable. The machinery by which the diurnal movement of the sphere is followed, must be especially modified to suit each eccentric career. This, too, was done, and on June 30, 1881, Janssen secured a perfect photograph of the brilliant object then visible, showing the structure of the tail with beautiful distinctness to a distance of 2-1/2° from the head. An impression to nearly 10° was obtained about the same time by Dr. Henry Draper at New York, with an exposure of 162 minutes.[1299]

Tebbutt's (or comet 1881 iii.) was also the first comet of which the spectrum was so much as attempted to be chemically recorded. Both Huggins and Draper were successful in this respect, but Huggins was more completely so.[1300] The importance of the feat consisted in its throwing open to investigation a part of the spectrum invisible to the eye, and so affording an additional test of cometary constitution. The result was fully to confirm the origin from carbon-compounds assigned to the visible rays, by disclosing additional bands belonging to the same series in the ultra-violet; as well as to establish unmistakably the presence of a not inconsiderable proportion of reflected solar light by the clear impression of some of the principal Fraunhofer lines. Thus the polariscope was found to have told the truth, though not the whole truth.

The photograph so satisfactorily communicative was taken by Sir William Huggins on the night of June 24; and on the 29th, at Greenwich, the tell-tale Fraunhofer lines were perceived to interrupt the visible range of the spectrum. This was at first so vividly continuous, that the characteristic cometary bands could scarcely be detached from their bright background. But as the nucleus faded towards the end of June, they came out strongly, and were more and more clearly seen, both at Greenwich and at Princeton, to agree, not with the spectrum of hydro-carbons glowing in a vacuum tube, but with that of the same substances burning in a Bunsen flame.[1301] It need not, however, be inferred that cometary materials are really in a state of combustion. This, from all that we know, may be called an impossibility. The additional clue furnished was rather to the manner of their electrical illumination.[1302]

The spectrum of the tail was, in this comet, found to be not essentially different from that of the head. Professor Wright of Yale College ascertained a large percentage of its light to be polarized in a plane passing through the sun, and hence to be reflected sunlight.[1303] A faint continuous spectrum corresponded to this portion of its radiance; but gaseous emissions were also present. At Potsdam, on June 30, the hydro-carbon bands were indeed traced by Vogel to the very end of the tail;[1304] and they were kept in sight by Young at a greater distance from the nucleus than the more equably dispersed light. There seems little doubt that, as in the solar corona, the relative strength of the two orders of spectra is subject to fluctuations.

The comet of 1881 iii. was thus of signal service to science. It afforded, when compared with the comet of 1807, the first undeniable example of two such bodies travelling so nearly in the same orbit as to leave absolutely no doubt of the existence of a genetic tie between them. Cometary photography came to its earliest fruition with it; and cometary spectroscopy made a notable advance by means of it. Before it was yet out of sight, it was provided with a successor.

At Ann Arbor Observatory, Michigan, on July 14, a comet was discovered by Dr. Schaeberle, which, as his claim to priority is undisputed, is often allowed to bear his name, although designated, in strict scientific parlance, comet 1881 iv. It was observed in Europe after three days, became just discernible by the naked eye at the end of July, and brightened consistently up to its perihelion passage, August 22, when it was still about fifty million miles from the sun. During many days of that month, the uncommon spectacle was presented of two bright comets circling together, though at widely different distances, round the North pole of the heavens. The newcomer, however, never approached the pristine lustre of its predecessor. Its nucleus, when brightest, was comparable to the star Cor Caroli, a narrow, perfectly straight ray proceeding from it to a distance of 10°. This was easily shown by Brédikhine to belong to the hydrogen type of tails;[1305] while a "strange, faint second tail, or bifurcation of the first one," observed by Captain Noble, August 24,[1306] fell into the hydro-carbon class of emanations. It was seen, August 22 and 24, by Dr. F. Terby of Louvain,[1307] as a short nebulous brush, like the abortive beginning of a congeries of curving trains; but appeared no more. Its well-attested presence was significant of the complex constitution of such bodies, and the manifold kinds of action progressing in them.

The only peculiarity in the spectrum of Schaeberle's comet consisted in the almost total absence of continuous light. The carbon-bands were nearly isolated and very bright. Barely from the nucleus proceeded a rainbow-tinted streak, indicative of solid or liquid matter, which, in this comet, must have been of very scanty amount. Its visit to the sun in 1881 was, so far as is known, the first. The elements of its orbit showed no resemblance to those of any previous comet, nor any marked signs of periodicity. So that, although it may be considered probable, we do not *know* that it is moving in a closed curve, or will ever again penetrate the precincts of the solar system. It was last seen from the southern hemisphere, October 19, 1881.

The third of a quartette of lucid comets visible within sixteen months, was discovered by Mr. C. S. Wells at the Dudley Observatory, Albany, March 17, 1882. Two days later it was described by Mr. Lewis Boss as "a great comet in miniature," so well defined and regularly developed were its various parts and appendages. Discernible with optical aid early in May, it was on June 5 observed on the meridian at Albany just before noon—an astronomical event of extreme rarity. Comet Wells, however, never became an object so conspicuous as to attract general attention, owing to its immersion in the evening twilight of our northern June.

But the study of its spectrum revealed new facts of the utmost interest. All the comets till then examined had been found (with the two transiently observed exceptions already mentioned) to conform to one invariable type of luminous emission. Individual distinctions there had been, but no specific differences. Now all these bodies had kept at a respectful distance from the sun; for of the great comet of 1880 no spectroscopic inquiries had been made. Comet Wells, on the other hand, approached its surface within little more than five million miles on June 10, 1882; and the vicinity had the effect of developing a novel feature in its incandescence.

During the first half of April its spectrum was of the normal type, though the carbon bands were unusually weak; but with approach to the sun they died out, and the entire light seemed to become concentrated into a narrow, unbroken, brilliant streak, hardly to be distinguished from the spectrum of a star. This unusual behaviour excited attention, and a strict watch was kept. It was rewarded at the Dunecht Observatory, May 27, by the discernment of what had never before been seen in a comet—the yellow ray of sodium.[1308] By June 1, this had kindled into a blaze overpowering all other emissions. The light of the comet was practically monochromatic; and the image of the entire head, with the root of the tail, could be observed, like a solar prominence, depicted, in its new saffron vesture of vivid illumination, within the jaws of an open slit.

At Potsdam, the bright yellow line was perceived with astonishment by Vogel on May 31, and was next evening identified with Fraunhofer's "D." Its character led him to infer a very considerable density in the glowing vapour emitting it.[1309] Hasselberg founded an additional argument in favour of the electrical origin of cometary light on the changes in the spectrum of comet Wells.[1310] For they were closely paralleled by some earlier experiments of Wiedemann, in which the gaseous spectra of vacuum tubes were at once effaced on the introduction of metallic vapours. It seemed as if the metal had no sooner been rendered volatile by heat, than it usurped the entire office of carrying the discharge, the resulting light being thus exclusively of its production. Had simple incandescence by heat been in question, the effect would have been different; the two spectra would have been superposed without prejudice to either. Similarly, the replacement of the hydro-carbon bands in the spectrum of the comet by the sodium line proved electricity to be the exciting agent. For the increasing thermal power of the sun might, indeed, have ignited the sodium, but it could not have extinguished the hydro-carbons.

Sir William Huggins succeeded in photographing the spectrum of comet Wells by an exposure of one hour and a quarter.[1311] The result was to confirm the novelty of its character. None of the ultra-violet carbon groups were apparent; but certain bright rays, as yet unidentified, had imprinted themselves. Otherwise the spectrum was strongly continuous, uninterrupted even by the Fraunhofer lines detected in the spectrum of Tebbutt's comet. Hence it was concluded that a smaller proportion of reflected light was mingled with the native emissions of the later arrival.

All that is certainly known about the *extent* of the orbit traversed by the first comet of 1882 is that it came from, and is now retreating towards, vastly remote depths of space. An American computer[1312] found a period indicated for it of no less than 400,000 years; A. Thraen of Dingelstädt arrived at one of 3617.[1313] Both are perhaps equally insecure.

We have now to give some brief account of one of the most remarkable cometary apparitions on record, and—with the single exception of that identified with the name of Halley—the most instructive to astronomers. The lessons learned from it were as varied and significant as its aspect was splendid; although from the circumstance of its being visible in general only before sunrise, the spectators of its splendour were comparatively few.

The discovery of a great comet at Rio Janeiro, September 11, 1882, became known in Europe through a telegram from M. Cruls, director of the observatory at that place. It had, however (as appeared subsequently), been already seen on the 8th by Mr. Finlay of the Cape Observatory, and at Auckland as early as September 3. A later, but very singularly conditioned detection, quite unconnected with any of the preceding, was effected by Dr. Common at Ealing. Since the eclipse of May 17, when a comet—named "Tewfik" in honour of the Khedive of Egypt—was caught on Dr. Schuster's photographs, entangled, one might almost say, in the outer rays of the corona, he had scrutinized the neighbourhood of the sun on the infinitesimal chance of intercepting another such body on its rapid journey thence or thither. We record with wonder that, after an interval of exactly four months, that infinitesimal chance turned up in his favour.

On the forenoon of Sunday, September 17, he saw a great comet close to, and rapidly approaching the sun. It was, in fact, then within a few hours of perihelion. Some measures of position were promptly taken; but a cloud-veil covered the interesting spectacle before mid-day was long past. Mr. Finlay at the Cape was more completely fortunate. Divided from his fellow-observer by half the world, he unconsciously finished, under a clearer sky, his interrupted observation. The comet, of which the silvery radiance contrasted strikingly with the reddish-yellow glare of the sun's margin it drew near to, was followed "continuously right into the boiling of the limb"—a circumstance without precedent in cometary history.[1314] Dr. Elkin, who watched the progress of the event with another instrument, thought the intrinsic brilliancy of the nucleus scarcely surpassed by that of the sun's surface. Nevertheless it had no sooner touched it than it vanished as if annihilated. So sudden was the disappearance (at 4h. 50m. 58s., Cape mean time), that the comet was at first believed to have passed *behind* the sun. But this proved not to have been the case. The observers at the Cape had witnessed a genuine transit. Nor could non-visibility be explained

PLATE III.

The Great Comet of September, 1882.

The Great Comet of September, 1882.

Photographed at the Royal Observatory, Cape of Good Hope

by equality of lustre. For the gradations of light on the sun's disc are amply sufficient to bring out against the dusky background of the limb any object matching the brilliancy of the centre; while an object just equally luminous with the limb must inevitably show dark at the centre. The only admissible view, then, is that the bulk of the comet was of too filmy a texture, and its presumably solid nucleus too small, to intercept any noticeable part of the solar rays—a piece of information worth remembering.

On the following morning, the object of this unique observation showed (in Sir David Gill's words) "an astonishing brilliancy as it rose behind the mountains on the east of Table Bay, and seemed in no way diminished in brightness when the sun rose a few minutes afterward. It was only necessary to shade the eye from direct sunlight with the hand at arm's length, to see the comet, with its brilliant white nucleus and dense white, sharply bordered tail of quite half a degree in length."[1315] All over the world, wherever the sky was clear during that day, September 18, it was obvious to ordinary vision. Since 1843 nothing had been seen like it. From Spain, Italy, Algeria, Southern France, despatches came in announcing the extraordinary appearance. At Cordoba, in South America, the "blazing star near the sun" was the one topic of discourse.[1316] Moreover—and this is altogether extraordinary—the records of its daylight visibility to the naked eye extend over three days. At Reus, near Tarragona, it showed bright enough to be seen through a passing cloud when only three of the sun's diameters from his limb, just before its final rush past perihelion on September 17; while at Carthagena in Spain, on September 19, it was kept in view during two hours before and two hours after noon, and was similarly visible in Algeria on the same day.[1317]

But still more surprising than the appearance of the body itself were the nature and relations of the path it moved in. The first rough elements computed for it by Mr. Tebbutt, Dr. Chandler, and Mr. White, assistant at the Melbourne Observatory, showed at once a striking resemblance to those of the twin comets of 1843 and 1880. This suggestive fact became known in this country, September 27, through the medium of a Dunecht circular. It was fully confirmed by subsequent inquiries, for which ample opportunities were luckily provided. The likeness was not, indeed, so absolutely perfect as in the previous case; it included some slight, though real differences; but it bore a strong and unmistakable stamp, broadly challenging explanation.

Two hypotheses only were really available. Either the comet of 1882 was an accelerated return of those of 1843 and 1880, or it was a fragment of an original mass to which they also had belonged. For the purposes of the first view the "resisting medium" was brought into full play; the opinion of its efficacy was for some time both prevalent and popular, and formed the basis, moreover, of something of a sensational panic. For a comet which, at a single passage through the sun's atmosphere, encountered sufficient resistance to shorten its period from thirty-seven to two years and eight months, must, in the immediate future, be brought to rest on his surface; and the solar conflagration thence ensuing was represented in some quarters, with more licence of imagination than countenance from science, as likely to be of catastrophic import to the inhabitants of our little planet.

But there was a test available in 1882 which it had not been possible to apply either in 1843 or in 1880. The two bodies visible in those years had been observed only after they had already passed perihelion;[1318] the third member of the group, on the other hand, was accurately followed for a week before that event, as well as during many months after it. Finlay's and Elkin's observation of its disappearance at the sun's edge formed, besides, a peculiarly delicate test of its motion. The opportunity was thus afforded, by directly comparing the comet's velocity before and after its critical plunge through the solar surroundings, of ascertaining with approximate certainty whether any considerable retardation had been experienced in the course of that plunge. The answer distinctly given was that there had not. The computed and observed places on both sides of the sun fitted harmoniously together. The effect, if any were produced, was too small to be perceptible.

This result is, in itself, a memorable one. It seems to give the *coup de grâce* to Encke's theory—discredited, in addition, by Backlund's investigation—of a resisting medium growing rapidly denser inwards. For the perihelion distance of the comet of 1882, though somewhat greater than that of its predecessors, was nevertheless extremely small. It passed at less than 300,000 miles of the sun's surface. But the ethereal substance long supposed to obstruct the movement of Encke's comet would there be nearly 2,000 times denser than at the perihelion of the smaller body, and must have exerted a conspicuous retarding influence. That none such could be detected seems to argue that no such medium exists.

Further evidence of a decisive kind was not wanting on the question of identity. The "Great September Comet" of 1882 was in no hurry to withdraw itself from curious terrestrial scrutiny. It was discerned with the naked eye at Cordoba as late as March 7, 1883, and still showed in the field of the great equatoreal on June 1 as an "excessively faint whiteness."[1319] It was then about 480 millions of miles from the earth—a distance to which no other comet—not even excepting the peculiar one of 1729—had been pursued.[1320] Moreover, an arc of 340 out of the entire 360 degrees of its circuit had been described under the eyes of astronomers; so that its course came to be very well known. That its movement is in a very eccentric ellipse, traversed in several hundred years, was ascertained.[1321] The later inquiries of Dr. Kreutz,[1322] completed in a volume published in 1901,[1323] demonstrated the period to be of about 800 years, while that of its predecessor in 1843 might possibly agree with it, but is much more probably estimated at 512 years. The hypothesis that they, or any of the comets associated with them, were returns of an individual body is peremptorily excluded. They may all, however, have been separated from one original mass by the divellent action of the sun at close quarters. Each has doubtless its own period, since each has most likely suffered retardations or accelerations special to itself, which, though trifling in amount, would avail materially to alter the length of the major axis, while leaving the remaining elements of the common orbit virtually unchanged.[1324]

A fifth member was added to the family in 1887. On the 18th of January in that year, M. Thome discovered at Cordoba a comet reproducing with curious fidelity the lineaments of that observed in the same latitudes seven years previously. The narrow ribbon of light, contracting towards the sun, and running outward from it to a distance of thirty-five degrees; the unsubstantial head—a veiled nothingness, as it appeared, since no distinct nucleus could be made out; the quick fading into invisibility, were all accordant peculiarities, and they were confirmed by some rough calculations of its orbit, showing geometrical affinity to be no less unmistakable than physical likeness. The observations secured were indeed, from the nature of the apparition, neither numerous nor over-reliable; and the earliest of them dated from a week after perihelion, passed, almost by a touch-and-go escape, January 11. On January 27, this mysterious object could barely be discerned telescopically at Cordoba.[1325] That it belonged to the series of "southern comets" can scarcely be doubted; but the inference that it was an actual return of the comet of 1880, improbable in itself, was negatived by its non-appearance in 1894. Meyer's incorporation with this extraordinary group of the "eclipse-comet" of 1882[1326] has been approved by Kreutz, after searching examination.

The idea of cometary systems was first suggested by Thomas Clausen in 1831.[1327] It was developed by the late M. Hoek, director of the Utrecht Observatory, in 1865 and some following years.[1328] He found that in quite a considerable number of cases, the paths of two or three comets had a common point of intersection far out in space, indicating with much likelihood a community of origin. This consisted, according to his surmise, in the disruption of a parent mass during its sweep round the star latest visited. Be this as it may, the fact is undoubted that numerous comets fall into groups, in which similar conditions of motion betray a pre-existent physical connection. Never before, however, had geometrical relationship been so notorious as between the comets now under consideration; and never before, in a comet still, it might be said, in the prime of life, had physical peculiarities tending to account for that affinity been so obvious as in the chief member of the group.

Observation of a granular structure in cometary nuclei dates far back into the seventeenth century, when Cysatus and Hevelius described the central parts of the comets of 1618 and 1652 respectively as made up of a congeries of minute stars. Analogous symptoms of a loose state of aggregation have of late been not unfrequently detected in telescopic comets, besides the instances of actual division offered by those connected with the names of Biela and Liais. The forces concerned in producing these effects seem to have been peculiarly energetic in the great comet of 1882.

The segmentation of the nucleus was first noticed in the United States and at the Cape of Good Hope, September 30. It proceeded rapidly. At Kiel, on October 5 and 7, Professor Krüger perceived two centres of condensation. A definite and progressive separation into *three* masses was observed by Professor Holden, October 13 and 17.[1329] A few days later, M. Tempel found the head to consist of *four* lucid aggregations, ranged nearly along the prolongation of the caudal axis;[1330] and Dr. Common, January 27, 1883, saw *five* nuclei in a line "like pearls on a string."[1331] This remarkable character was preserved to the last moment of the comet's distinct visibility. It was a consequence, according to Dr. Kreutz, of violent interior action in the comet itself While close to the sun.

There were, however, other curious proofs of a disaggregative tendency in this body. On October 9, Schmidt discovered at Athens a nebulous object 4° south-west of the great comet, and travelling in the same direction. It remained visible for a few days, and, from Oppenheim's and Hind's calculations, there can be little doubt that it was really the offspring by fission of the body it accompanied.[1332] This is rendered more probable by the unexampled spectacle offered, October 14, to Professor Barnard, then of Nashville, Tennessee, of *six or eight* distinct cometary masses within 6° south by west of the comet's head, none of which reappeared on the next opportunity for a search.[1333] A week later, however, one similar object was discerned by Mr. W. R. Brooks, in the opposite direction from the comet. Thus space appeared to be strewn with the filmy débris of this beautiful but fragile structure all along the track of its retreat from the sun.

Its tail was only equalled (if it were equalled) in length by that of the comet of 1843. It extended in space to the vast distance of 200 millions of miles from the head; but, so imperfectly were its proportions displayed to terrestrial observers, that it at no time covered an arc of the sky of more than 30°. This apparent extent was attained, during a few days previous to September 25, by a faint, thin, rigid streak, noticed only by a few observers—by Elkin at the Cape Observatory, Eddie at Grahamstown, and Cruls at Rio Janeiro. It diverged at a low angle from the denser curved train, and was produced, according to Brédikhine,[1334] by the action of a repulsive force twelve times as strong as the counter-pull of gravity. It belonged, that is, to type 1; while the great bifurcate appendage, obvious to all eyes, corresponded to the lower rate of emission characteristic of type 2. This was remarkable for the perfect definiteness of its termination, for its strongly-forked shape, and for its unusual permanence. Down to the end of January, 1883, its length, according to Schmidt's observations, was still 93 million miles; and a week later it remained visible to the naked eye, without notable abridgment.

Most singular of all was an anomalous extension of the appendage *towards* the sun. During the greater part of October and November, a luminous "tube" or "sheath," of prodigious dimensions, seemed to surround the head, and project in a direction nearly opposite to that of the usual outpourings of attentuated matter. (See Plate III.) Its diameter was computed by Schmidt to be, October 15, no less than four million miles, and it was described by Cruls as a “truncated cone of nebulosity,” stretching 3° or 4° sunwards.[1335] This, and the entire anterior part of the comet, were again surrounded by a thin, but enormously voluminous paraboloidal envelope, observed by Schiaparelli for a full month from October 19.[1336] There can be little doubt that these abnormal effluxes were a consequence of the tremendous physical disturbance suffered at perihelion; and it is worth remembering that something analogous was observed in the comet of 1680 (Newton’s), also noted for its excessively close approach to the sun, and possibly moving in a related orbit. The only plausible hypothesis as to the mode of their production is that of an opposite state of electrification in the particles composing the ordinary and extraordinary appendages.

The spectrum of the great comet of 1882 was, in part, a repetition of that of its immediate predecessor, thus confirming the inference that the previously unexampled sodium-blaze was in both a direct result of the intense solar action to which they were exposed. But the D line was, this time, not seen alone. At Dunecht, on the morning of September 18, Drs. Copeland and J. G. Lohse succeeded in identifying six brilliant rays in the green and yellow with as many prominent iron-lines;[1337] a very significant addition to our knowledge of cometary constitution, and one which lent countenance to Brédikhine’s assumption of various kinds of matter issuing from the nucleus with velocities inversely as their atomic weights. All the lines equally showed a slight displacement, indicating a recession from the earth of the radiating body at the rate of 37 to 46 miles a second. A similar observation, made by M. Thollon at Nice on the same day, gave emphatic sanction to the spectroscopic method of estimating movement in the line of sight. Before anything was as yet known of the comet’s path or velocity, he announced, from the position of the double sodium-line alone, that at 3 p.m. on September 18 it was increasing its distance from our planet by from 61 to 76 kilometres per second.[1338] M. Bigourdan’s subsequent calculations showed that its actual swiftness of recession was at that moment 73 kilometres.

Changes in the inverse order to those seen in the spectrum of comet Wells soon became apparent. In the earlier body, carbon bands had died out with *approach* to perihelion, and had been replaced by sodium emissions; in its successor, sodium emissions became weakened and disappeared with *retreat* from perihelion, and found their substitute in carbon bands. Professor Riccò was, in fact, able to infer, from the sequence of prismatic phenomena, that the comet had already passed the sun; thus establishing a novel criterion for determining the position of a comet in its orbit by the varying quality of its radiations.

Recapitulating what was learnt from the five conspicuous comets of 1880-82, we find that the leading facts acquired to science were these three. First, that comets may be met with pursuing each other, after intervals of many years, in the same, or nearly the same, track; so that identity of orbit can no longer be regarded as a sure test of individual identity. Secondly, that at least the outer corona may be traversed by such bodies with perfect apparent impunity. Finally, that their chemical constitution is highly complex, and that they possess, in some cases at least, a metallic core resembling the meteoric masses which occasionally reach the earth from planetary space.

A group of five comets, including Halley's, own a sort of cliental dependence upon the planet Neptune. They travel out from the sun just to about his distance from it, as if to pay homage to a powerful protector, who gets the credit of their establishment as periodical visitors to the solar system. The second of these bodies to affect a looked-for return was a comet—the sixteenth within ten years—discovered by Pons, July 20, 1812, and found by Encke to revolve in an elliptic orbit, with a period of nearly 71 years. It was not, however, until September 1, 1883, that Mr. Brooks caught its reappearance; it passed perihelion January 25, and was last seen June 2, 1884. At its brightest, it had the appearance of a second magnitude star, furnished with a poorly developed double tail, and was fairly conspicuous to the naked eye in Southern Europe, from December to March. One exceptional feature distinguished it. Its fluctuations in form and luminosity were unprecedented in rapidity and extent. On September 21, Dr. Chandler[1339] observed it at Harvard as a very faint, diffused nebulosity, with slight central condensation. On the next night, there was found in its place a bright star of the eighth magnitude, scarcely marked out, by a bare trace of environing haze, from the genuine stars it counterfeited. The change was attended by an eight-fold augmentation of light, and was proved by Schiaparelli's confirmatory observations[1340] to have been accomplished within a few hours. The stellar disguise was quickly cast aside. The comet appeared on September 23 as a wide nebulous disc, and soon after faded down to its original dimness. Its distance from the sun was then no less than 200 million miles, and its spectrum showed nothing unusual. These strange variations recurred slightly on October 15, and with marked emphasis on January 1, when they were witnessed with amazement, and photometrically studied by Müller of Potsdam.[1341] The entire cycle this time was run through in less than four hours—the comet having, in that brief space, condensed, with a vivid outburst of light, into a seeming star, and the seeming star having expanded back again into a comet. Scarcely less transient, though not altogether similar, changes of aspect were noted by M. Perrotin,[1342] January 13 and 19, 1884. On the latter date, the continuous spectrum given by a reddish-yellow disc surrounding the true nucleus seemed intensified by bright knots corresponding to the rays of sodium.

A comet discovered by Mr. Sawerthal at the Royal Observatory, Cape of Good Hope, February 19, 1888, distinguished itself by blazing up, on May 19, to four or five times its normal brilliancy, at the same time throwing out from the head two lustrous lateral branches.[1343] These had, on June 1, spread backward so as to join the tail, with an effect like the playing of a fountain; ten or eleven days later, they had completely disappeared, leaving the comet in its former shape and insignificance. Its abrupt display of vitality occurred two full months after perihelion.

On the morning of July 7, 1889, Mr. W. R. Brooks, of Geneva, New York, eminent as a successful comet-hunter, secured one of his customary trophies. The faint object in question was moving through the constellation Cetus, and turned out to be a member of Jupiter's numerous family of comets, revolving round the sun in a period of seven years. Its past history came then, to a certain extent, within the scope of investigation, and proved to have been singularly eventful; nor had the body escaped scatheless from the vicissitudes to which it had been exposed. Observing from Mount Hamilton, August 2 and 5, Professor Barnard noticed this comet (1889, v.) to be attended in its progress through space by four *outriders*, "The two brighter companions" (the fainter pair survived a very short time) "were perfect miniatures," Professor Barnard tells us,[1344] "of the larger comet, each having a small, fairly defined head and nucleus, with a faint, hazy tail, the more distant one being the larger and less developed. The three comets were in a straight line, nearly east and west, their tails lying along this line. There was no connecting nebulosity between these objects, the tails of the two smaller not reaching each other, or the large comet. To all appearance they were absolutely independent comets." Nevertheless, Spitaler, at Vienna, in the early days of August, perceived, as it were, a thin cocoon of nebulosity woven round the entire trio.[1345] One of them faded from view September 5; the other actually outshone the original comet on August 31, but was plainly of inferior vitality. It was last seen by Barnard on November 25, with the thirty-six inch refractor, while its primary afforded an observation for position with the twelve-inch, March 20, 1890.[1346] A cause for the disruption it had presumably undergone had, before then, been plausibly assigned.

The adventures of Lexell's comet have long served to exemplify the effects of Jupiter's despotic sway over such bodies. Although bright enough in 1770 to be seen with the naked eye, and ascertained to be circulating in five and a half years, it had never previously been seen, and failed subsequently to present itself. The explanation of this anomaly, suggested by Lexell, and fully confirmed by the analytical inquiries both of Laplace and Leverrier,[1347] was that a very close approach to Jupiter in 1767 had completely changed the character of its orbit, and brought it within the range of terrestrial observation; while in 1779, after having only twice traversed its new path (at its second return it was so circumstanced as to be invisible from the earth), it was, by a fresh encounter, diverted into one entirely different. Yet the possibility was not lost sight of that the great planet, by inverting its mode of action, might undo its own work, and fling the comet once more into the inner part of the solar system. This possibility seemed to be realized by Chandler's identification of Brooks's and Lexell's comet.[1348] An exceedingly close approach to Jupiter in 1886 had, he found reason to believe, produced such extensive alterations in the elements of its motion as to bring the errant body back to our neighbourhood in 1889. But his inference, though ratified by Mr. Charles Lane Poor's preliminary calculations, proved dubious on closer inquiry, and was rendered wholly inadmissible by the circumstances attending the return of Brooks's comet in 1896.[1349]

The companion-objects watched by Barnard in 1889 had by that time, perhaps, become dissipated in space, for they were not redetected. They represented, in all likelihood, wreckage from a collision with Jupiter, dating, perhaps, so far back as 1791, when Mr. Lane Poor found that one of the fateful meetings to which short-period comets are especially subject had taken place.

The Lexell-Brooks case was almost duplicated by the resemblance to De Vico's lost comet of 1844[1350] of one detected November 20, 1894, by Edward, son of Lewis Swift. Schulhof[1351] announced the identity, and Chandler,[1352] under reserve, vouched for it. Had the comet continued to pursue the track laboriously laid down for it at Boston, and shown itself at the due epoch in 1900, its individuality might have been considered assured; but the formidable vicegerent of the sun once more interposed, and, in 1897, swept it out of the terrestrial range of view. Hence the recognition remains ambiguous.

On the morning of March 7, 1892, Professor Lewis Swift discovered the brightest comet that had been seen by northern observers since 1882. About the time of perihelion, which occurred on April 6, it was conspicuous, as it crossed the celestial equator from Aquarius towards Pegasus, with a nucleus equal to a third magnitude star, and a tail twenty degrees long. This tail was multiple, and multiple in a most curiously variable manner. It divided up into many thin nebulous streaks, the number and relative lustre of which underwent rapid and marked changes. Their permanent record on Barnard's and W. H. Pickering's plates marked a noteworthy advance in cometary photography. Plate IV. reproduces two of the Lick pictures, taken with a six-inch camera, on April 5 and 7 respectively, with, in each case, an exposure of about one hour. The tail is in the first composed of three main branches, the middle one having sprung out since the previous morning, and the branches are, in their turn, split up into finer rays, to the number of perhaps a dozen in all. In the second a very different state of things is exhibited. "The southern component," Professor Barnard remarked, "which was the brightest on the 5th, had become diffused and fainter, while the middle tail was very bright and broad. Its southern side, which was the best defined, was wavy in numerous places, the tail appearing as if disturbing currents were flowing at right angles to it. At 42° from the head the tail made an abrupt bend towards the south, as if its current was deflected by some obstacle. In the densest portion of the tail, at the point of deflection, are a couple of dark holes, similar to those seen in some of the nebulæ. The middle portion of the tail is brighter, and looks like crumpled silk in places."[1353] Next morning the southern was the prominent branch, and it was loaded, at 1° 42′ from the head, with a strange excrescence, suggesting the budding-out of a fresh comet in that incongruous situation.[1354] Some of these changes, Professor Barnard thought, might possibly be explained by a rotation of the tail on an axis passing through the nucleus, and Pickering, who formed a similar opinion on independent

PLATE IV.

Photographs of Swift's Comet.

1 2

Photographs of Swift's Comet. By Professor E. E. Barnard. No. 1. Taken April 4, 1892; exposure 1 h. No. 2. Taken April 6, 1892; exposure 1 h. 5 m

grounds, assigned about 94 hours as the period of the gyrating movement.[1355] He, moreover, determined accelerative velocities outward from the sun of definite condensations in the tail, indicating for its materials, on Brédikhine's theory, a density less than one half that of hydrogen.[1356] This conclusion applied also to Rordame's comet, which exhibited a year later phenomena analogous to those remarked in Swift's. Their photographic study led Professor Hussey[1357] to significant inferences as to the structure and rapid changes of cometary appendages.

Seven comets were detected in 1892, and all, strange to say, were visible together towards the close of the year.[1358] Among them was a faint object, which unexpectedly left a trail on a plate exposed by Professor Barnard to the stars in Aquila[1359] on October 12. This was the first comet actually discovered by photography, the Sohag comet having been simultaneously seen and pictured. It has a period of about six years. Holmes's comet is likewise periodical, in rather less than seven years. Its path, which is wholly comprised between the orbits of Mars and Jupiter, is less eccentric than that of any other known comet. Subsequently to its discovery, on November 6, it underwent some curious vicissitudes. At first bright and condensed, it expanded rapidly with increasing distance from the sun (to which it had made its nearest approach on June 13), until, by the middle of December, it was barely discernible with powerful telescopes as "a feebly luminous mist on the face of the sky."[1360] But on January 16, 1893, observers in Europe and America were bewildered to find, as if substituted for it, a yellow star of the seventh magnitude, enveloped in a thin nebulous husk, which enclosed a faint miniature tail.[1361] This condensation and recovery of light lasted in its full intensity only a couple of days. The almost evanescent faintness of Holmes's comet at its next return accounted for its invisibility previous to 1892, when it was evidently in a state of peculiar excitement. Mr. Perrine was barely able, with the Lick 36-inch, to find the vague nebulous patch which occupied its predicted place on June 10, 1899.

The origin of comets has been long and eagerly inquired into, not altogether apart from the cheering guidance of ascertained facts. Sir William Herschel regarded them as fragments of nebulæ[1362]—scattered débris of embryo worlds; and Laplace approved of and adopted the idea.[1363] But there was a difficulty. No comet has yet been observed to travel in a decided hyperbola. The typical cometary orbit, apart from disturbance, is parabolic—that is to say, it is indistinguishable from an enormously long ellipse. But this circumstance could only be reconciled with the view that the bodies thus moving were casual visitors from outer space, by making, as Laplace did, the tacit assumption that the solar system was at rest. His reasoning was, indeed, thereby completely vitiated, as Gauss pointed out in 1815;[1364] and the objections then urged were reiterated by Schiaparelli,[1365] who demonstrated in 1871 that a large preponderance of well-marked hyperbolic orbits should result if comets were picked up *en route* by a swiftly-advancing sun. The fact that their native movement is practically parabolic shows it to have been wholly imparted from without. They passively obeyed the pull exerted upon them. In other words, their condition previous to being attracted by the sun was one very nearly of relative repose.[1366] They shared, accordingly, the movement of translation through space of the solar system.

This significant conclusion had been indicated, on other grounds, as the upshot of researches undertaken independently by Carrington[1367] and Mohn[1368] in 1860, with a view to ascertaining the anticipated existence of a relationship between the general *lie* of the paths of comets and the direction of the sun's journey. It is tolerably obvious that if they wander at haphazard through interstellar regions their apparitions should markedly aggregate towards the vicinity of the constellation Lyra; that is to say, we should meet considerably more comets than would overtake us, for the very same reason that falling stars are more numerous after than before midnight. Moreover, the comets met by us should be, apparently, swifter-moving objects than those coming up with us from behind; because, in the one case, our own real movement would be added to, in the other subtracted from, theirs. But nothing of all this can be detected. Comets approach the sun indifferently from all quarters, and with velocities quite independent of direction.

We conclude, then, that the "cosmical current" which bears the solar system towards its unknown goal carries also with it nebulous masses of undefined extent, and at an undefined remoteness, fragments detached from which, continually entering the sphere of the sun's attraction, flit across our skies under the form of comets. These are, however, almost certainly so far strangers to our system that they had no part in the long processes of development by which its present condition was attained. They are, perhaps, survivals of an earlier, and by us scarcely and dimly conceivable state of things, when the swirling chaos from which sun and planets were, by a supreme edict, to emerge, had not as yet separately begun to be.

FOOTNOTES:

[1267] *Astr. Nach.*, Nos. 1,172-4.

[1268] *Berichte Sächs. Ges.*, 1871, p. 174.

[1269] *Natur der Cometen*, p. 124; *Astr. Nach.*, No. 2,086.

[1270] *Annales de l'Obs. de Moscou*, t. iii., pt. i., p. 37.

[1271] *Bull. Astr.*, t. iii., p. 598. The value of the repellent force for the comet of 1811 (which offered peculiar facilities for its determination) was found = 17·5.

[1272] Faye, *Comptes Rendus*, t. xciii., p. 13.

[1273] *Annales*, t. v., pt. ii., p. 137.

[1274] *Am. Jour. of Sc.*, vol. xxxii. (2nd ser.), p. 57.

[1275] *Astr. Nach.*, No. 2,082.

[1276] *Annales de l’Obs. de Moscou*, t. vi., pt. i., p. 60.

[1277] *Astr. Register*, March, 1883.

[1278] *Astr. Nach.*, No. 3,018.

[1279] *Ibid.*, No. 3,093.

[1280] *Constitution de l’Espace Céleste*, p. 224.

[1281] *Astroph. Jour.*, vol. iii., p. 36.

[1282] *Physikalische Zeitschrift*, November 10 and 17, 1900; *Astroph. Jour.*, vol. xiii., p. 344. *Cf.* Schwarzschild, *Sitzungsb.*, München, 1901, Heft iii.; J. Hahn, *Nature*, vols. lxv., p. 415; lxvi., p. 55.

[1283] *Astr. Nach.*, No. 2,307.

[1284] *Ibid.*, No. 2,304.

[1285] *Observatory*, vol. iii., p. 390.

[1286] *Astr. Nach.*, No. 2,319.

[1287] *Ueber die Kometen von 371 v. Chr.*, 1668, 1843, I. und 1880 I. Göttingen, 1880.

[1288] *Meteor.*, lib. i., cap. 6.

[1289] *Mém. Soc. Phys. de Genève*, t. xxviii., p. 23.

[1290] *Annales de l’Obs. de Moscou*, t. vii., pt. i., p. 60.

[1291] Brédikhine, *Annales*, t. viii., p. 68.

[1292] *Am. Jour. of Sc.*, vol. xxii., p. 305.

[1293] Messrs. Burton and Green observed a dilatation of the stellar image into a nebulous patch by the transmission of its rays through a nuclear jet of the comet. *Am. Jour. of Sc.*, vol. xxii., p. 163.

[1294] *Archives des Sciences*, t. viii., p. 535. *Cf.* Perrine’s negative results for Swift’s comet in 1899, *Astr. Nach.*, No. 3,602.

[1295] Riem concluded in 1896 for a definitive period of 2,429 years; *Observatory*, vol. xix., p. 282.

[1296] Holden, *Publ. Astr. Pac. Soc.*, vol. ix., p. 89.

[1297] *Annuaire*, Paris, 1882, p. 781.

[1298] *Annuaire*, 1882, p. 766.

[1299] *Am. Jour. of Sc.*, vol. xxii., p. 134.

[1300] *Report Brit. Assoc.*, 1881, p. 520.

[1301] *Month. Not.*, vol. xlii., p. 14; *Am. Jour. of Sc.*, vol. xxii., p. 136.

[1302] Piazzi Smyth, *Nature*, vol. xxiv., p. 430.

[1303] *Astr. Nach.*, No. 2,395.

[1304] *Ibid.*

[1305] *Astr. Nach.*, No. 2,411.

[1306] *Month. Not.*, vol. xlii., p. 49.

[1307] *Astr. Nach.*, No. 2,414.

[1308] *Copernicus*, vol. ii., p. 229.

[1309] *Astr. Nach.*, Nos. 2,434, 2,437.

[1310] *Ibid.*, No. 2,441.

[1311] *Report Brit. Assoc.*, 1882, p. 442.

[1312] J. J. Parsons, *Am. Jour. of Science*, vol. xxvii., p. 34.

[1313] *Astr. Nach.*, No. 2,441.

[1314] *Observatory*, vol. v., p. 355. The transit had been foreseen by Mr. Tebbutt, but it occurred after sunset in New South Wales.

[1315] *Observatory*, vol. v., p. 354.

[1316] Gould, *Astr. Nach.*, No. 2,481.

[1317] Flammarion, *Comptes Rendus*, t. xcv., p. 558.

[1318] Captain Ray's sextant observation of the comet of 1843, a few hours before perihelion, was too rough to be of use.

[1319] *Astr. Nach.*, No. 2,538.

[1320] *Nature*, vol. xxix., p. 135.

[1321] *Astr. Nach.*, No. 2,482.

[1322] *Vierteljahrsschrift Astr. Ges.*, Jahrg. xxiv., p. 308; *Bull. Astr.*, t. vii., p. 513.

[1323] *Observatory*, vol. xxiv., p. 167.

[1324] The attention of the author was kindly directed to this point by Professor Young of Princeton (N. J.). *Cf.* Rebeur-Paschwitz, *Sirius*, Bd. xvi., p. 233.

[1325] Oppenheim, *Astr. Nach.*, No. 2,902.

[1326] *Astr. Nach.*, No. 2,717.

[1327] Gruithuisen's *Analekten*, Heft 7, p. 48.

[1328] *Month. Not.*, vols. xxv., xxvi., xxviii. *Cf.* Plummer, *Observatory*, vol. xiii., p. 263.

[1329] *Nature*, vol. xxvii., p. 246.

[1330] *Astr. Nach.*, No. 2,468.

[1331] *Athenæum*, February 3, 1883.

[1332] *Astr. Nach.*, Nos. 2,462, 2,466.

[1333] *Ibid.*, No. 2,489.

[1334] *Annales*, Moscow, t. ix., pt. ii., p. 52.

[1335] *Comptes Rendus*, t. xcvii., p. 797.

[1336] *Astr. Nach.*, No. 2,966.

[1337] *Copernicus*, vol. ii., p. 235.

[1338] *Comptes Rendus*, t. xcvi., p. 371.

[1339] *Astr. Nach.*, No. 2,553.

[1340] *Ibid.*

[1341] *Astr. Nach.*, No. 2,568.

[1342] *Annales de l'Observatoire de Nice*, t. ii., c. 53.

[1343] Fényi, *Astr. Nach.*, No. 2,844; Kammermann, *Ibid.*, No. 2,849.

[1344] *Publ. Astr. Pac. Soc.*, vol. i., p. 72.

[1345] *Annuaire*, Paris, 1891, p. 301.

[1346] *Astr. Nach.*, No. 2,989.

[1347] *Comptes Rendus*, t. xxv., p. 564.

[1348] *Astr. Journ.*, Nos. 205, 231.

[1349] *Ibid.*, Nos. 228, 244, 380.

[1350] *Observatory*, vol. xviii., pp. 60, 163 (Denning and Lynn).

[1351] *Astr. Nach.*, No. 3,267; Plummer, *Knowledge*, vol. xix., p. 156.

[1352] *Astr. Jour.*, Nos. 333, 338.

[1353] *Astr. and Astroph.*, vol. xi., p. 387.

[1354] *Knowledge*, vol. xv., p. 299.

[1355] *Harvard Annals*, vol. xxxii., pt. ii., p. 272.

[1356] *Ibid.*, p. 287.

[1357] *Publ. Astr. Pac. Soc.*, vol. vii., p. 161.

[1358] H. C. Wilson, *Astr. and Astroph.*, vol. xii., p. 121.

[1359] *Observatory*, vol. xvi., p. 92.

[1360] Barnard, *Astr. and Astroph.*, vol. xii., p. 180; *Astroph. Jour.*, vol. iii., p. 41.

[1361] Palisa, *Astr. Nach.*, No. 3,147; Denning, *Observatory*, vol. xvi., p. 142.

[1362] *Phil. Trans.*, vol. ci., p. 306.

[1363] *Conn. des Temps*, 1816, p. 213.

[1364] *Œuvres*, t. vi., p. 581.

[1365] *Mem. dell' Istit. Lombardo*, t. xii., p. 164; *Rendiconti*, t. vii., p. 77, 1874.

[1366] W. Förster, *Pop. Mitth.*, 1879, p. 7; Fabry, *Étude sur la Probabilité des Comètes Hyperboliques*, Marseille, 1893, p. 158.

[1367] *Mem. R. A. Soc.*, vol. xxix., p. 335.

[1368] *Month. Not.*, vol. xxiii., p. 203.

CHAPTER XII

STARS AND NEBULÆ

That a science of stellar chemistry should not only have become possible, but should already have made material advances, is assuredly one of the most amazing features in the swift progress of knowledge our age has witnessed. Custom can never blunt the wonder with which we must regard the achievement of compelling rays emanating from a source devoid of sensible magnitude through immeasurable distance, to reveal, by its distinctive qualities, the composition of that source. The discovery of revolving double stars assured us that the great governing force of the planetary movements, and of our own material existence, sways equally the courses of the farthest suns in space; the application of prismatic analysis certified to the presence in the stars of the familiar materials, no less of the earth we tread, than of the human bodies built up out of its dust and circumambient vapours.

We have seen that, as early as 1823, Fraunhofer ascertained the generic participation of stellar light in the peculiarity by which sunlight, spread out by transmission through a prism, shows numerous transverse rulings of interrupting darkness. No sooner had Kirchhoff supplied the key to the hidden meaning of those ciphered characters than it was eagerly turned to the interpretation of the dim scrolls unfolded in the spectra of the stars. Donati made at Florence in 1860 the first efforts in this direction; but with little result, owing to the imperfections of the instrumental means at his command. His comparative failure, however, was a prelude to others' success. Almost simultaneously, in 1862, the novel line of investigation was entered upon by Huggins near London, by Father Secchi at Rome, and by Lewis M. Rutherfurd in New York. Fraunhofer's device of using a cylindrical lens for the purpose of giving a second dimension to stellar spectra was adopted by all, and was, indeed, indispensable. For a luminous point, such as a star appears, becomes, when viewed through a prism, a variegated line, which, until broadened into a band by the intervention of a cylindrical lens, is all but useless for purposes of research. This process of *rolling out* involves, it is true, much loss of light—a scanty and precious commodity, as coming from the stars; but the loss is an inevitable one. And so fully is it compensated by the great light-grasping power of modern telescopes that important information can now be gained from the spectroscopic examination of stars far below the range of the unarmed eye.

The effective founders of stellar spectroscopy, then (since Rutherfurd shortly turned his efforts elsewhither), were Father Secchi, the eminent Jesuit astronomer of the Collegio Romano, where he died, February 26, 1878, and Sir William Huggins, with whom the late Professor W. A. Miller was associated. The work of each was happily directed so as to supplement that of the other. With less perfect appliances, the Roman astronomer sought to render his extensive rather than precise; at Tulse Hill searching accuracy over a narrow range was aimed at and attained. To Father Secchi is due the merit of having executed the first spectroscopic survey of the heavens. Above 4,000 stars were passed in review by him, and classified according to the varying qualities of their light. His provisional establishment (1863-67) of four types of stellar spectra[1369] has proved a genuine aid to knowledge through the facilities afforded by it for the arrangement and comparison of rapidly accumulating facts. Moreover, it is scarcely doubtful that these spectral distinctions correspond to differences in physical condition of a marked kind.

The first order comprises more than half the visible and probably an overwhelming proportion of the faintest stars. Sirius, Vega, Regulus, Altair, are amongst its leading members. Their spectra are distinguished by the breadth and intensity of the four dark bars due to the absorption of hydrogen, and by the extreme faintness of the metallic lines, of which, nevertheless, hundreds are disclosed by careful examination. The light of these “Sirian” orbs is white or bluish; and it is found to be rich in ultra-violet rays.

Capella and Arcturus belong to the second, or solar type of stars, which is about one-sixth less numerously represented than the first. Their spectra are quite closely similar to that of sunlight, in being ruled throughout by innumerable fine dark lines; and they share its yellowish tinge.

The third class includes most red and variable stars (commonly synonymous), of which Betelgeux in the shoulder of Orion, and “Mira” in the Whale, are noted examples. Their characteristic spectrum is of the “fluted” description. It shows like a strongly illuminated range of seven or eight variously tinted columns seen in perspective, the light falling from the red end towards the violet. This *kind* of absorption is produced by the vapours of metalloids or of compound substances.

To the fourth order of stars belongs also a colonnaded spectrum, but *reversed*; the light is thrown the other way. The three broad zones of absorption which interrupt it are sharp towards the red, insensibly gradated towards the violet end. The individuals composing Class IV. are few and apparently insignificant, the brightest of them not exceeding the fifth magnitude. They are commonly distinguished by a deep red tint, and gleam like rubies in the field of the telescope. Father Secchi, who in 1867 detected the peculiarity of their analyzed light, ascribed it to the presence of carbon in some form in their atmospheres; and this was confirmed by the researches of H. C. Vogel,[1370] director of the Astro-physical Observatory at Potsdam. The hydro-carbon bands, in fact, seen bright in comets, are dark in these singular objects—the only ones in the heavens (save one bright-line star and a rare meteor)[1371] which display a cometary analogy of the fundamental sort revealed by the spectroscope.

The members of all four orders are, however, emphatically suns. They possess, it would appear, photospheres radiating all kinds of light, and differ from each other mainly in the varying qualities of their absorptive atmospheres. The principle that the colours of stars depend, not on the intrinsic nature of their light, but on the kinds of vapours surrounding them, and stopping out certain portions of that light, was laid down by Huggins in 1864.[1372] The phenomena of double stars seem to indicate a connection between the state of the investing atmospheres, by the action of which their often brilliantly contrasted tints are produced, and their mutual physical relations. A tabular statement put forward by Professor Holden in June, 1880,[1373] made it, at any rate, clear that inequality of magnitude between the components of binary systems accompanies unlikeness in colour, and that stars more equally matched in one respect are pretty sure to be so in the other. Besides, blue and green stars of a decided tinge are never solitary; they invariably form part of systems. So that association has undoubtedly a predominant influence upon colour.

Nevertheless, the crude notion thrown out by Zöllner in 1865,[1374] that yellow and red stars are simply white stars in various stages of cooling, obtained for a time undeserved currency. D'Arrest, indeed, protested against it, and Ångström, in 1868,[1375] substituted atmospheric quality for mere colour[1376] as a criterion of age and temperature. His lead was followed by Lockyer in 1873,[1377] and by Vogel in 1874.[1378] The scheme of classification due to the Potsdam astro-physicist differed from Father Secchi's only in presenting his third and fourth types as subdivisions of the same order, and in inserting three subordinate categories; but their variety was "rationalised" by the addition of the seductive idea of progressive development. Thus, the white Sirian stars were represented as the *youngest* because the hottest of the sidereal family; those of the solar pattern as having already wasted much of their store by radiation, and being well advanced in middle life; while the red stars with banded spectra figured as effete suns, hastening rapidly down the road to final extinction.

Vogel's scheme is, however, incomplete. It traces the downward curve of decay, but gives no account of the slow ascent to maturity. The present splendour of Vega, for instance, was prepared, according to all creative analogy, by almost endless processes of gradual change. What was its antecedent condition? The question has been variously answered. Dr. Johnstone Stoney advocated, in 1867, the comparative youth of red stars;[1379] A. Ritter, of Aix-la-Chapelle, divided them, in 1883,[1380] into two squadrons, posted, the one on the ascending, the other on the descending branch of the temperature-curve, and corresponding, presumably, with Secchi's third and fourth orders of stars with banded spectra. Whether, in the interim, they should display spectra of the Sirian or of the solar type was made to depend on their greater or less massiveness.[1381] But the relation actually existing perhaps inverts that contemplated by Ritter. Certainly, the evidence collected by Mr. Maunder in 1891 strongly supports the opinion that the average solar star is a weightier body than the average Sirian star.[1382]

On November 17, 1887, Sir Norman Lockyer communicated to the Royal Society the first of a series of papers embodying his "Meteoritic Hypothesis" of cosmical constitution, stated and supported more at large in a separate work bearing that name, published in

1890. The fundamental proposition wrought out in it was that "all self-luminous bodies in the celestial space are composed either of swarms of meteorites or of masses of meteoric vapour produced by heat."[1383] On the basis of this supposed community of origin, sidereal objects were distributed in seven groups along a temperature-curve ascending from nebulæ and gaseous, or bright-line stars, through red stars of the third type, and a younger division of solar stars, to the high Sirian level; then descending through the more strictly solar stars to red stars of the fourth type ("carbon-stars"), below which lay only the *caput mortuum* entitled Group vii. The ground-work of this classification was, however, insecure, and has given way. Certain spectroscopic coincidences, avowedly only approximate, suggesting that stars and nebulæ of every species might be formed out of variously aggregated meteorites, failed of verification by exact inquiry. And spectroscopic coincidences admit of no compromise. Those that are merely approximate are, as a rule, unmeaning.

In his Presidential Address at the Cardiff Meeting of the British Association in 1891, Dr. Huggins adhered in the main to the line of advance traced by Vogel. The inconspicuousness of metallic lines in the spectra of the white stars he attributed, not to the paucity, but to the high temperature of the vapours producing them, and the consequent deficiency of contrast between their absorption-rays and the continuous light of the photospheric background. "Such a state of things would more probably," in his opinion, "be found in conditions anterior to the solar stage," while "a considerable cooling of the sun would probably give rise to banded spectra due to compounds." He adverted also to the influential effects upon stellar types of varying surface gravity, which being a function of both mass and bulk necessarily gains strength with wasting heat and consequent shrinkage. The same leading ideas were more fully worked out in "An Atlas of Representative Stellar Spectra," published by Sir William and Lady Huggins in 1899. They were, moreover, splendidly illustrated by a set of original spectrographic plates, while precision was added to the adopted classification by the separation of helium from hydrogen stars. The spectrum of the exotic substance terrestrially captured in 1895 is conspicuous by absorption, as Vogel, Lockyer, and Deslandres promptly recognised in a considerable number of white stars, among them the Pleiades and most of the brilliants in Orion. Mr. McClean, whose valuable spectrographic survey of the heavens was completed at the Cape in 1897, found reason to conclude that they are in the first stage of development from gaseous nebulæ;[1384] and in this the Tulse Hill investigators unhesitatingly concur.

The strongest evidence for the primitive state of white stars is found in their nebular relations. The components of groups, still involved and entangled with "silver braids" of cosmic mist, show, perhaps invariably, spectra of the helium type, occasionally crossed by bright rays. Possibly all such stars have passed through a bright-line stage; but further evidence on the point is needed. Relative density furnishes another important test of comparative age, and Sirian stars are, on the whole, undoubtedly more bulky proportionately to their mass than solar stars. The rule, however, seems to admit of exceptions; hence the change from one kind of spectrum to the other is not inevitably connected with the attainment of a particular degree of condensation. There is reason to believe that it is anticipated in the more massive globes, despite their comparatively slow cooling, as a consequence of the greater power of gravity over their investing vaporous envelopes. This conclusion is enforced by the relations of double-star spectra. The fact that, in unequal pairs, the chief star most frequently shows a solar, its companion a Sirian, spectrum can scarcely be otherwise explained than by admitting that, while the sequence of types is pursued in an invariable order, it is pursued much more rapidly in larger than in small orbs. It need not, indeed, be supposed that all stars are identical in constitution, and present identical life-histories.[1385] Individualities in the one, and divergencies in the other, must be allowed for. Yet the main track is plainly continuous, and leads by insensible gradations from nebulæ through helium stars to the Sirian, and onward to the solar type, whence, by an inevitable transition, fluted, or "Antarian,"[1386] spectra develop.

The first-known examples of the class of gaseous stars—β Lyræ and γ Cassiopeiæ—were noticed by Father Secchi at the outset of his spectroscopic inquiries. Both show *bright* lines of hydrogen and helium, so that the peculiarity of their condition probably consists in the intense ignition of their chromospheric surroundings. Their entire radiating surfaces might be described as *faculous*. That is to say, brilliant formations, such as have been photographed by Professor Hale on the sun's disc,[1387] cover, perhaps, the whole, instead of being limited to a small portion of the photospheric area. But this state of things is more or less inconstant. Some at least of the bright rays indicative of it are subject to temporary extinctions. Already in 1871-72, Dr. Vogel[1388] suspected the prevalence of such vicissitudes; and their reality was ascertained by M. Eugen von Gothard. After the completion of his new astrophysical observatory at Herény in the autumn of 1881, he repeatedly observed the spectra of both stars without perceiving a trace of bright lines; and was thus taken quite by surprise when he caught a twinkling of the crimson C in γ Cassiopeiæ, August 13, 1883.[1389] A few days later, the whole range including D_3 was lustrous. Duly apprised of the recurrence of a phenomenon he had himself vainly looked for during some years, M. von Konkoly took the opportunity of the great Vienna refractor being placed at his disposal to examine with it the relighted spectrum on August 27.[1390] In its wealth of light C was dazzling; D_3 and the green and blue hydrogen rays shone somewhat less vividly; D and the group *b* showed faintly dark; while three broad absorption-bands, sharply terminated towards the red, diffuse towards the violet, shaded the spectrum near its opposite extremities.

The previous absence of bright lines from the spectrum of this star was, however, by no means so protracted or complete as M. von Gothard supposed. At Dunecht, C was "superbly visible" December 20, 1879[1391]; F was seen bright on October 28 of the same year, and frequently at Greenwich in 1880-81. The curious fact has, moreover, been adverted to by Dr. Copeland, that C *is much more variable than F*. To Vogel, June 18, 1872, the first was invisible, while the second was bright; at Dunecht, January 11, 1887, the conditions were so far inverted that C was resplendent, F comparatively dim.

No spectral fluctuations were detected in γ Cassiopeiæ by Keeler in 1889; but even with the giant telescope of Mount Hamilton, the helium-ray was completely invisible.[1392] It made, nevertheless, capricious appearances at South Kensington during that autumn, and again October 21, 1894,[1393] while in September, 1892, Bélopolsky could obtain no trace of it on orthochromatic plates exposed with the 30-inch Pulkowa refractor.[1394] Still more noteworthy is the circumstance that the well-known green triplet of magnesium (*b*), recorded as dark by Keeler in 1889, came out bright on fifty-two spectrographs of the star taken by Father Sidgreaves during the years 1891-99.[1395] No fluctuations in the hydrogen-spectrum were betrayed by them; but subordinate lines of unknown origin showed alternate fading and vivification.

The spectrum of β Lyræ undergoes transitions to some extent analogous, yet involving a different set of considerations. First noticed by Von Gothard in 1882,[1396] they were imperfectly made out, two years later, to be of a cyclical character.[1397] This, however, could only be effectively determined by photographic means. Beta Lyræ is a "short-period variable." Its light changes with great regularity from 3·4 to 4·4 magnitude every twelve days and twenty-two hours, during which time it attains a twofold maximum, with an intervening secondary minimum. The question, then, is of singular interest, whether the changes of spectral quality visible in this object correspond to its changes in visual brightness. A distinct answer in the affirmative was supplied through Mrs. Fleming's examination of the Harvard plates of the star's spectrum, upon which, in 1891, she found recorded diverse complex changes of bright and dark lines obviously connected with the phases of luminous variation, and obeying, in the long-run, precisely the same period.[1398] Something more will be said presently as to the import of this discovery.

Bright hydrogen lines have so far been detected—for the most part photographically at Harvard College—in about sixty stars, including Pleione, the surmised lost Pleiad, P Cygni, noted for instability of light in the seventeenth century, and the extraordinary southern variable, η Carinæ. In most of these objects other vivid rays are associated with those due to hydrogen. A blaze of hydrogen, moreover, accompanies the recurring outbursts of about one hundred and fifty "long-period variables," giving banded spectra of the third type. Professor Pickering discovered the first example of this class, towards the close of 1886, in Mira Ceti; further detections were made visually by Mr. Espin; and the conjunction of bright hydrogen-lines with dusky bands has been proved by Mrs. Fleming's long experience in studying the Harvard photographs, to indicate unerringly the subjection of the stars thus characterised to variations of lustre accomplished in some months.

A third variety of gaseous star is named after MM. Wolf and Rayet, who discovered, at Paris in 1867,[1399] its three typical representatives, close together in the constellation Cygnus. Six further specimens were discovered by Dr. Copeland, five of them in the course of a trip for the exploration of visual facilities in the Andes in 1883;[1400] and a large number have been made known through spectral photographs taken in both hemispheres under Professor Pickering's direction. At the close of the nineteenth century, over a hundred such objects had been registered, none brighter than the sixth magnitude, with the single exception of γ Argûs, the resplendent continuous spectrum of which, first examined by Respighi and Lockyer in 1871, is embellished with the yellow and blue rays distinctive of the type.[1401] Here, then, we have a stellar globe apparently at the highest point of sunlike incandescence, sharing the peculiarities of bodies verging towards the nebulous state. Examined with instruments of adequate power, their spectra are seen to be highly complex. They include a fairly strong continuous element, a numerous set of absorption-lines, and a range of emission-lines, more or less completely represented in different stars. Especially conspicuous is a broad effluence of azure light, found by Dr. Vogel in 1883,[1402] and by Sir William and Lady Huggins in 1890,[1403] to be of multiple structure, and hence to vary in its mode of display. Its suggested identification with the blue carbon-fluting was disproved at Tulse Hill. Metallic vapours give no certain sign of their presence in the atmospheres of these remarkable bodies; but nebulum is stated to shine in some.[1404] Hydrogen and helium account for a large proportion of their spectral rays. Thirty-two Wolf-Rayet stars were investigated, spectroscopically and spectrographically, by Professor Campbell with the great Lick refractor in 1892-94;[1405] and several disclosed the singularity, already noticed by him in γ Argûs, of giving out mixed series, the members of which change from vivid to obscure with increase of refrangibility. It is difficult to imagine by what chromospheric machinery this curious result can be produced. Alcyone in the Pleiades presents the same characteristic. Alone among the hydrogen lines, crimson C glows in its spectrum, while all the others are dark. Luminosity of the Wolf-Rayet kind is particularly constant, both in quantity and quality. It seems to be incapable of developing save under galactic conditions. All the stars marked by it lie near the central line of the Milky Way, or in the Magellanic Clouds. They tend also to gather into groups. Circles of four degrees radius include respectively seven in Argo, eight in Cygnus.

The first spectroscopic star catalogue was published by Dr. Vogel at Potsdam in 1883.[1406] It included 4,051 stars, distributed over a zone of the heavens extending from 20° north to 20° south of the celestial equator.[1407] More than half of these were white stars, while red stars with banded spectra occurred in the proportion of about one-thirteenth of the whole. To the latter genus, M. Dunér, then of Lund, now Director of the Upsala Observatory, devoted a work of standard authority, issued at Stockholm in 1884. This was a catalogue with descriptive particulars of 352 stars showing banded spectra, 297 of which belong to Secchi's third, 55 to his fourth class (Vogel's iii. *a* and iii. *b*). Since then discovery has progressed so rapidly, at first through the telescopic reviews of Mr. Espin, then in the course of the photographic survey carried on at Harvard College, that considerably over one thousand stars are at present recognised as of the family of Betelgeux and Mira, while about 250 have so far exhibited the spectral pattern of 19 Piscium. One fact well ascertained as regards both species is the invariability of the type. The prismatic flutings of the one, and the broader zones of the other, are as if stereotyped—they undergo, in their fundamental outlines, no modification, though varying in relative intensity from star to star. They are always accompanied by, or superposed upon, a spectrum of dark lines, in producing which sodium and iron have an obvious share; and certain bright rays, noticed by Secchi with imperfect appliances as enhancing the chiaroscuro effects in carbon-stars, came out upon plates exposed by Hale and Ellerman in 1898 with the stellar spectrograph of the Yerkes Observatory.[1408] Their genuineness was shortly afterwards visually attested by Keeler, Campbell, and Dunér;[1409] but no chemical interpretation has been found for them.

A fairly complete preliminary answer to the question, What are the stars made of? was given by Sir William Huggins in 1864.[1410] By laborious processes of comparison between stellar dark lines and the bright rays emitted by terrestrial substances, he sought to assure his conclusions, regardless of cost in time and pains. He averred, indeed, that—taking into account restrictions by weather and position—the thorough investigation of a *single* star-spectrum would be the work of some years. Of two, however—those of Betelgeux and Aldebaran—he was able to furnish detailed and accurate drawings. The dusky flutings in the prismatic light of the first of these stars have not been identified with the absorption of any particular substance; but associated with them are metallic lines, of which 78 were measured, and a good many identified by Huggins, while the wave-lengths of 97 were determined by Vogel in 1871.[1411] A photographic research, made by Keeler at the Alleghany Observatory in 1897, convinced him that the linear spectrum of third-type stars of the Betelgeux pattern essentially repeats that of the sun, but with marked differences in the comparative strength of its components.[1412] Hydrogen rays are inconspicuously present. That an exalted temperature reigns, at least in the lower strata of the atmosphere, is certified by the vaporisation there of matter so refractory to heat as iron.[1413]

Nine elements—among them iron, sodium, calcium, and magnesium—were recognised by Huggins as having stamped their signature on the spectrum of Aldebaran; while the existence in Sirius, and nearly all the other stars inspected, of hydrogen, together with sundry metals, was rendered certain or highly probable. This was admitted to be a bare gleaning of results; nor is there reason to suppose any of his congeners inferior to our sun in complexity of constitution. Definite knowledge on the subject, however, made little advance beyond the point to which it was brought by Huggins's early experiments until spectroscopic photography became thoroughly effective as a means of research.

In this, as in so many other directions, Sir William Huggins acted as pioneer. In March, 1863, he obtained microscopic prints of the spectra of Sirius and Capella.[1414] But they told nothing. No lines were visible in them. They were mere characterless streaks of light.

Nine years later Dr. Henry Draper of New York got an impression of four lines in the spectrum of Vega. Then Huggins attacked the subject again in 1876, when the 18-inch speculum of the Royal Society had come into his possession, using prisms of Iceland spar and lenses of rock crystal; and this time with better success. A photograph of the spectrum of Vega showed seven strong lines.[1415] Still he was not satisfied. He waited and worked for three years longer. At length, on December 18, 1879, he was able to communicate to the Royal Society[1416] results answering to his expectations. The delicacy of eye and hand needed to obtain them may be estimated from the single fact that the image of a star had to be kept, by continual minute adjustments, exactly projected upon a slit 1/350 of an inch in width during nearly an hour, in order to give it time to imprint the characters of its analyzed light upon a gelatine plate raised to the highest pitch of sensitiveness. But by this time he had secured in his wife a rarely qualified assistant.

The ultra-violet spectrum of the white stars—of which Vega was taken as the type—was thus shown to be a very remarkable one. A group of broad dark lines intersected it, arranged at intervals diminishing regularly upward, and falling into a rhythmical succession with the visible hydrogen lines. All belonged presumably to the same substance; and the presumption was rendered a certainty by direct photographs of the hydrogen spectrum taken by H. W. Vogel at Berlin a few months earlier.[1417] In them seven of the white-star series of grouped lines were visible; and the full complement of twelve appeared on Cornu's plates in 1886.[1418]

In yellow stars, such as Capella and Arcturus, the same rhythmical series was *partially* represented, but associated with a great number of other lines; their state, as regards ultra-violet absorption, approximating to that of the sun; while the redder stars betrayed so marked a deficiency in actinic rays that from Betelgeux, with an exposure *forty times* that required for Sirius, only a faint spectral impression could be obtained, and from Aldebaran, in the strictly invisible region, almost none at all.

Thus, by the means of stellar light-analysis, acquaintance was first made with the ultra-violet spectrum of hydrogen;[1419] and its harmonic character, as expressed by "Balmer's Law," supplies a sure test for discriminating, among newly discovered lines, those that appertain from those that are unrelated to it. Deslandres' five additional prominence-rays, for instance, were at once seen to make part of the series, because conforming to its law;[1420] while a group of six dusky bands, photographed by Sir William and Lady Huggins, April 4, 1890,[1421] near the extreme upper end of the spectrum of Sirius, were pronounced without hesitation, for the opposite reason, to have nothing to do with hydrogen. Their true affinities are still a matter for inquiry.

As regards the hydrogen spectrum, however, the stars had further information in reserve. Until recently, it was supposed to consist of a single harmonic series, although, by analogy, three should co-exist. In 1896, accordingly, a second, bound to the first by unmistakable numerical relationships, was recognised by Professor Pickering in spectrographs of the 2·5 magnitude star ζ Puppis,[1422] and the identification was shortly afterwards extended to prominent Wolf-Rayet emission lines. The discovery was capped by Dr. Rydberg's indication of the Wolf-Rayet blue band at λ 4,688 as the fundamental member of the third, and principal, hydrogen series.[1423] None of the "Pickering lines" (as they may be called to distinguish them from the "Huggins series") can be induced to glimmer in vacuum-tubes. They seem to characterise bodies in a primitive state,[1424] and are in many cases associated with absorption rays of oxygen, the identification of which by Mr. McClean in 1897[1425] was fully confirmed by Sir David Gill.[1426] The typical "oxygen star" is β Crucis, one of the brilliants of the Southern Cross; but the distinctive notes of its spectrum occur in not a few specimens of the helium class. Thus, Sir William and Lady Huggins photographed several ultra-violet oxygen lines in β Lyræ,[1427] and found in Rigel signs of the presence of nitrogen,[1428] which, as well as silicium, proves to be a tolerably frequent constituent of such orbs.[1429] For some unknown reason, metalloids tend to become effaced, as metals, in the normal course of stellar development, exert a more and more conspicuous action.

Dr. Scheiner's spectrographic researches at Potsdam in 1890 and subsequently, exemplify the immense advantages of self-registration. In a restricted section of the spectrum of Capella, he was enabled to determine nearly three hundred lines with more precision than had then been attained in the measurement of terrestrial spectra. This star appeared to be virtually identical with the sun in physical constitution, although it emits, according to the best available data, about 140 times as much light, and is hence presumably 1,600 times more voluminous. An equally close examination of the spectrum of Betelgeux showed the predominance in it of the linear absorption of iron;[1430] but its characteristic flutings do not extend to the photographic region. Spectra of the second and third orders are for this reason not easily distinguished on the sensitive plate.

A spectrographic investigation of all the brighter northern stars was set on foot in 1886 at the observatory of Harvard College, under the form of a memorial to Dr. H. Draper, whose promising work in that line was brought to a close by his premature death in 1882. No individual exertions could, however, have realized a tithe of what has been and is being accomplished under Professor Pickering's able direction, with the aid of the Draper and other instruments, supplemented by Mrs. Draper's liberal provision of funds. A novel system was adopted, or, rather, an old one—originally used by Fraunhofer—was revived.[1431] The use of a slit was discarded as unnecessary for objects like the stars, devoid of sensible dimensions, and giving hence a *naturally* pure spectrum; and a large prism, placed in front of the object-glass, analysed at once, with slight loss of light, the rays of all the stars in the field. Their spectra were taken, as it were, wholesale. As many as two hundred stars down to the eighth magnitude were occasionally printed on a single plate with a single exposure. No cylindrical lens was employed. The movement of the stars themselves was turned to account for giving the desirable width to their spectra. The star was allowed—by disconnecting or suitably regulating the clock—to travel slowly across the line of its own dispersed light, so broadening it gradually into a band. Excellent results were secured in this way. About fifty lines appear in the photographed spectrum of Aldebaran, and eight in that of Vega. On January 26, 1886, with an exposure of thirty-four minutes, a simultaneous impression was obtained of the spectra (among many others) of close upon forty Pleiades. With few and doubtful exceptions, they all proved to belong to the same type. An additional argument for the common origin of the stars forming this beautiful group was thus provided.[1432]

The "Draper Catalogue" of stellar spectra was published in 1890.[1433] It gives the results of a rapid analytical survey of the heavens north of 25° of southern declination, and includes 10,351 stars, down to about the eighth magnitude. The telescope used was of eight inches aperture and forty-five focus, its field of view—owing to the "portrait-lens" or "doublet" form given to it—embracing with fair definition no less than one hundred square degrees. An objective prism eight inches square was attached, and exposures of a few minutes were given to the most sensitive plates that could be procured. In this way the sky was twice covered in duplicate, each star appearing, as a rule, on four plates. The registration of their spectra was sought to be made more distinctive than had previously been attempted, Secchi's first type being divided into four, his second into five subdivisions; but the differences regarded in them could be confidently established only for stars above the sixth magnitude. The work supplies none the less valuable materials for general inferences as to the distribution and relations of the spectral types. The labour of its actual preparation was borne by a staff of ladies under the direction of Mrs. Fleming. Materials for its completion to the southern pole have been accumulated with the identical instrument used at Cambridge, transferred for the purpose in 1889 to Peru, and the forthcoming "Second Draper Catalogue" will comprise 30,000 stars in both hemispheres. As supplements to this great enterprise, two important detailed discussions of stellar spectra were issued in 1897 and 1901 respectively.[1434] The first, by Miss A. C. Maury, dealt with 681 bright stars visible in the northern hemisphere; the second, by Miss A. J. Cannon, with 1,122 southern stars. Both authors traced, with care and ability, the minute gradations by which the long process of stellar evolution appears to be accomplished.

The progress of the Draper Memorial researches was marked by discoveries of an unexampled kind.

The principle upon which "motion in the line of sight" can be detected and measured with the spectroscope has already been explained.[1435] It depends, as our readers will remember, upon the removal of certain lines, dark or bright (it matters not which), from their normal places by almost infinitesimal amounts. The whole spectrum of the moving object, in fact, is very slightly *shoved* hither or thither, according as it is travelling towards or from the eye; but, for convenience of measurement, one line is usually picked out from the rest, and attention concentrated upon it. The application of this method to the stars, however, is encompassed with difficulties. It needs a powerfully dispersive spectroscope to show line-displacements of the minute order in question; and powerful dispersion involves a strictly proportionate enfeeblement of light. This, where the supply is already to a deplorable extent niggardly, can ill be afforded; for which reason the operation of determining a star's approach or recession is, even apart from atmospheric obstacles, an excessively delicate one.

It was first executed by Sir William Huggins early in 1868.[1436] Selecting the brightest star in the heavens as the most promising subject of experiment, he considered the F line in the spectrum of Sirius to be just so much displaced towards the red as to indicate (the orbital motion of the earth being deducted) recession at the rate of twenty-nine miles a second; and the reality and direction of the movement were ratified by Vogel and Lohse's observation, March 22, 1871, of a similar, but even more considerable displacement.[1437] The inquiry was resumed by Huggins with improved apparatus in the following year, when the velocities of thirty stars were approximately determined.[1438] The retreat of Sirius, which proved slower than had at first been supposed, was now announced to be shared, at rates varying from twelve to twenty-nine miles, by Betelgeux, Rigel, Castor, Regulus, and five of the principal stars in the Plough. Arcturus, on the contrary, gave signs of rapid approach, as well as Pollux, Vega, Deneb in the Swan, and the brightness of the Pointers.

Numerically, indeed, these results were encompassed with uncertainty. Thus, Arcturus is now fully ascertained to be travelling towards the sun at the comparatively slow pace of less than five miles a second; and Sirius moves twice as fast in the same direction. The great difficulty of measuring so distended a line as the Sirian F might, indeed, well account for some apparent anomalies. The scope of Sir William Huggins's achievement was not, however, to provide definitive data, but to establish as practicable the method of procuring them. In this he was thoroughly successful, and his success was of incalculable value. Spectroscopic investigations of stellar movements may confidently be expected to play a leading part in the unravelment of the vast and complex relations which we can dimly detect as prevailing among the innumerable orbs of the sidereal world; for it supplements the means which we possess of measuring by direct observation movements transverse to the line of sight, and thus completes our knowledge of the courses and velocities of stars at ascertained distances, while supplying for all a valuable index to the amount of perspective foreshortening of apparent movement. Thus some, even if an imperfect, knowledge may at length be gained of the revolutions of the stars—of the systems they unite to form, of the paths they respectively pursue, and of the forces under the compulsion of which they travel.

The applicability of the method to determining the orbital motions of double stars was pointed out by Fox Talbot in 1871;[1439] but its use for their discovery revealed itself spontaneously through the Harvard College photographs. In "spectrograms" of ζ Ursæ Majoris (Mizar), taken in 1887, and again in 1889, the K line was seen to be double; while on other plates it appeared single. A careful study of Miss A. C. Maury of a series of seventy impressions indicated for the doubling a period of fifty-two days, and showed it to affect all the lines in the spectrum.[1440] The only available, and no doubt the true, explanation of the phenomenon was that two similar and nearly equal stars are here merged into one telescopically indivisible; their combined light giving a single or double spectrum, according as their orbital velocities are directed across or along our line of sight. The movements of a revolving pair of stars must always be opposite in sense, and proportionately equal in amount. That is, they at all times travel with speeds in the inverse ratio of their masses. Hence, unless the plane of their orbits be perpendicular to a plane passing through the eye, there must be two opposite points where their velocities in the line of sight reach a maximum, and two diametrically opposite points where they touch zero. The lines in their common spectrum would thus appear alternately double and single twice in the course of each revolution. To that of Mizar, at first supposed to need 104 days for its completion, a period of only twenty days fourteen hours was finally assigned by Vogel.[1441] Anomalous spectral effects, probably due to the very considerable eccentricity of the orbit, long impeded its satisfactory determination. The mean distance apart of the component stars, as now ascertained, is just twenty-two million miles, and their joint mass quadruples that of the sun. But these are minimum estimates. For if the orbital plane be inclined, much or little, to the line of sight, the dimensions and mass of the system should be proportionately increased.

An analogous discovery was made by Miss Maury in 1889. But in the spectrum of β Aurigæ, the lines open out and close up on alternate days, indicating a relative orbit[1442] with a radius of less than eight million miles, traversed in about four days. This implies a rate of travel for each star of sixty-five miles a second, and a combined mass 4·7 times that of the sun. The components are approximately equal, both in mass and light,[1443] and the system formed by them is transported towards us with a speed of some sixteen miles a second. The line-shiftings so singularly communicative proceed, in this star, with perfect regularity.

This new class of "spectroscopic binaries" could never have been visually disclosed. The distance of β Aurigæ from the earth, as determined, somewhat doubtfully, by Professor Pritchard, is nearly three and a third million times that of the earth from the sun (parallax = 0·06′); whence it has been calculated that the greatest angular separation of the revolving stars is only five-thousandths of a second of arc.[1444] To make this evanescent interval perceptible, a telescope eighty feet in aperture would be required.

The zodiacal star, Spica (α Virginis), was announced by Dr. Vogel, April 24, 1890,[1445] to belong to the novel category, with the difference, however, of possessing a nearly dark, instead of a brilliantly lustrous companion. In this case, accordingly, the tell-tale spectroscopic variations consist merely in a slight swinging to and fro of single lines. No second spectrum leaves a legible trace on the plate. Spica revolves in four days at the rate of fifty-seven miles a second,[1446] or quicker, in proportion as its orbit is more inclined to the line of sight, round a centre at a minimum distance of three millions of miles. But the position of the second star being unknown, the mass of the system remains indeterminate. The lesser component of the splendid, slowly revolving binary, Castor, is also closely double. Its spectral lines were found by Bélopolsky in 1896[1447] to oscillate once in nearly three days, the secondary globe being apparently quite obscure. Further study of the movements thus betrayed elicited the fact that the major axis of the eclipse traversed revolves in a period of 2,100 days, as a consequence, most likely, of the flattened shape of the stars.[1448] Still more unexpected was the simultaneous assignment, by Campbell and Newall, of a duplex character to Capella.[1449] Here both components shine, though with a different quality of light, one giving a pure solar spectrum, the other claiming prismatic affinity with Procyon. Their mutual circulation is performed in 104 days, and the radius of their orbit cannot be less, and may be a great deal more, than 51,000,000 miles. Hence the possibility is not excluded that the star—which has an authentic parallax of 0·08′—may be visually resolved. Indeed, signs of "elongation" were thought to be perceptible with the Greenwich 28-inch refractor,[1450] while only round images could be seen at Lick.[1451] Another noteworthy case is that of Polaris, found by Campbell to have certainly one, and probably two obscure attendants.[1452] Through his systematic investigations of stellar radial velocities with the Mills spectrograph, knowledge in this department has, since 1897, progressed so rapidly that the spectroscopic binaries of our acquaintance already number half a hundred, and ten times as many more doubtless lie within easy range of detection.

Now it is evident that a spectroscopic binary, if the plane of its motion made a very small angle with the line of sight, would be a variable star. For, during a few hours of each revolution, some at least of its light should be cut off by a transit of its dusky companion. Such "eclipse-stars" are actually found in the heavens.

The best and longest-known member of the group is Algol in the Head of Medusa, the "Demon-star" of the Arabs.[1453] This remarkable object, normally above the third magnitude, loses and regains three-fifths of its light once in 68·8 hours, the change being completed in about twelve hours. Its definite and limited nature, and punctual recurrence, suggested to Goodricke of York, by whom the periodicity of the star was discovered in 1783,[1454] the interposition of a large dark satellite. But the conditions involved by the explanation were first seriously investigated by Pickering in 1880.[1455] He found that the phenomena could be satisfactorily accounted for by supposing an obscure body 0·764 the bright star's diameter to revolve round it in a period identical with that of its observed variation. This theoretical forecast was verified with singular exactitude at Potsdam in 1889.[1456] A series of spectral photographs taken there showed each of Algol's minima to be preceded by a rapid recession from the earth, and succeeded by a rapid movement of approach towards it. They take place, accordingly, when the star is at the furthest point from ourselves of an orbit described round an invisible companion, the transits of which across its disc betray themselves to notice by the luminous vicissitudes they occasion. The diameter of this orbit, traversed at the rate of twenty-six miles a second, is just 2,000,000 miles; and it is an easy further inference from the duration and extent of the phases exhibited that Algol itself must be (in round numbers) one million, its attendant 830,000 miles in diameter. Assuming both to be of the same density, Vogel found their respective masses to be four-ninths and two-ninths that of the sun, and their distance asunder to be 3,230,000 miles.

This singularly assorted pair of stars possibly form part of a larger system. Their period of revolution is shorter now by six seconds than it was in Goodricke's time; and Dr. Chandler has shown, by an exhaustive discussion, that its inequalities are comprised in a cycle of about 130 years.[1457] They arise, in his view, from a common revolution, in that period, of the close couple about a third distant body, emitting little or no light, in an orbit inclined 20° to our line of vision, and of approximately the size of that described by Uranus round the sun. The time spent by light in crossing this orbit causes an apparent delay in the phases of the variable, when Algol and its eclipsing satellite are on its further side from ourselves, balanced by acceleration while they traverse its hither side. Dr. Chandler derives confirmation for his plausible and ingenious theory from a supposed undulation in the line traced out by Algol's small proper motion; but the reality of this disturbance has yet to be established.[1458] Meanwhile, M. Tisserand,[1459] late Director of the Paris Observatory, preferred to account for Algol's inequalities on the principle later applied by Bélopolsky to those of Castor. That is to say, he assumed a revolving line of apsides in an elliptical orbit traversed by a pretty strongly compressed pair of globes. The truth of this hypothesis can be tested by close observation of the phases of the star during the next few years.

The variable in the Head of Medusa is the exemplar of a class including 26 recognised members, all of which doubtless represent occulting combinations of stars. But their occultations result merely from the accident of their orbital planes passing through our line of sight; hence the heavens must contain numerous systems similarly constituted, though otherwise situated as regards ourselves, some of which, like Spica Virginis, will become known through their spectroscopic changes, while others, because revolving in planes nearly tangent to the sphere, or at right angles to the visual line, may never disclose to us their true nature. Among eclipsing stars should probably be reckoned the peculiar variables, β Lyræ and V Puppis, each believed to consist of a pair of bright stars revolving almost in contact.[1460] Three stars, on the other hand, distinguished by rapid and regular fluctuations, have been proved by Bélopolsky to be attended by non-occulting satellites, which circulate, nevertheless, in the identical periods of light-change.

Gore's "Catalogue of Known Variables"[1461] included, in 1884, 190 entries, and the number was augmented to 243 on its revision in 1888.[1462] Chandler's first list of 225 such objects,[1463] published about the same time, received successive expansions in 1893 and 1896,[1464] and finally included 400 entries. A new "Catalogue of Variable Stars," still wider in scope, will shortly be issued by the German *Astronomische Gesellschaft*. Mr. A. W. Roberts's researches on southern variables[1465] have greatly helped to give precision, while adding to the extent of knowledge in this branch. Dr. Gould held the opinion that most stars fluctuate slightly in brightness through surface-alterations similar to, but on a larger scale than those of the sun; and the solar analogy might be pushed somewhat further. It perhaps affords a clue to much that is perplexing in stellar behaviour. Wolf pointed out in 1852 the striking resemblance in character between curves representing sun-spot frequency and curves representing the changing luminous intensity of many variable stars. There were the same steep ascent to maximum and more gradual decline to minimum, the same irregularities in heights and hollows, and, it may be added, the same tendency to a double maximum, and complexity of superposed periods.[1466] It is impossible to compare the two sets of phenomena thus graphically portrayed without reaching the conclusion that they are of closely related origin. But the correspondence indicated is not, as has often been hastily assumed, between maxima of sun-spots and minima of stellar brightness, but just the reverse. The luminous outbursts, not the obscurations of variable stars, obey a law analogous to that governing the development of spots on the sun. Objects of the kind do not, then, gain light through the closing-up of dusky chasms in their photospheres, but by an actual increase of surface-brilliancy, together with an immense growth of these brilliant formations—prominences and faculæ—which, in the sun, accompany, or are appended to spots. A comparison of light-curves with curves of spot-frequency leaves no doubt on this point, and the strongest corroborative evidence is derived from the emergence of bright lines in the spectra of long-period variables rising to their recurring maxima.

Every kind and degree of variability is exemplified in the heavens. At the bottom of the scales are stars like the sun, of which the lustre is—tried by our instrumental means—sensibly steady. At the other extreme are ranged the astounding apparitions of "new," or "temporary" stars. Within the last thirty-six years eleven of these stellar guests (as the Chinese call them) have presented themselves, and we meet with a twelfth no farther back than April 27, 1848. But of the "new star" in Ophiuchus found by Mr. Hind on that night, little more could be learnt than of the brilliant objects of the same kind observed by Tycho and Kepler. The spectroscope had not then been invented. Let us hear what it had to tell of later arrivals.

About thirty minutes before midnight of May 12, 1866, Mr. John Birmingham of Millbrook, near Tuam, in Ireland, saw with astonishment a bright star of the second magnitude unfamiliarly situated in the constellation of the Northern Crown. Four hours earlier, Schmidt of Athens had been surveying the same part of the heavens, and was able to testify that it was not visible there. That is to say, a few hours, or possibly a few minutes, sufficed to bring about a conflagration, the news of which may have occupied hundreds of years in travelling to us across space. The rays which were its messengers, admitted within the slit of Sir William Huggins's spectroscope, May 16, proved to be of a composition highly significant as to the nature of the catastrophe. The star—which had already declined below the third magnitude—showed what was described as a double spectrum. To the dusky flutings of Secchi's third type four brilliant rays were added.[1467] The chief of these agreed in position with lines of hydrogen; so that the immediate cause of the outburst was inferred to have been the eruption, or ignition, of vast masses of that subtle kind of matter, the universal importance of which throughout the cosmos is one of the most curious facts revealed by the spectroscope.

T Coronæ (as the new star was called) quickly lost its adventitious splendour. Nine days after its discovery it was again invisible to the naked eye. It is now a pale yellow, slightly variable star near the tenth magnitude, and finds a place as such in Argelander's charts.[1468] It was thus obscurely known before it made its sudden leap into notoriety.

The next "temporary," discovered by Dr. Schmidt at Athens, November 24, 1876, could lay no claim to previous recognition even in that modest rank. It was strictly a parvenu. There was no record of its existence until it made its appearance as a star of nearly the third magnitude, in the constellation of the Swan. Its spectrum was examined, December 2, by Cornu at Paris,[1469] and a few days later by Vogel and O. Lohse at Potsdam.[1470] It proved of a closely similar character to that of T Coronæ. A range of bright lines, including those of hydrogen, and probably of helium, stood out from a continuous background impressed with strong absorption. It may be presumed that in reality the gaseous substances, which, by their sudden incandescence, had produced the apparent conflagration, lay comparatively near the surface of the star, while the screen of cooler materials intercepting large portions of its light was situated at a considerable elevation in its atmosphere.

The object, meanwhile, steadily faded. By the end of the year it was of no more than seventh magnitude. After the second week of March, 1877, strengthening twilight combined with the decline of its radiance to arrest further observation. It was resumed, September 2, at Dunecht, with a strange result. Practically the whole of its scanty light (it had then sunk below the tenth magnitude) was perceived to be gathered into a single bright line in the green, and that the most characteristic line of gaseous nebulæ.[1471] The star had, in fact, so far as outward appearance was concerned, become transformed into a planetary nebula, many of which are so minute as to be distinguishable from small stars only by the quality of their radiations. It is now, having sunk to about the fourteenth magnitude,[1472] entirely beyond the reach of spectroscopic scrutiny.

Perhaps none of the marvellous changes witnessed in the heavens has given a more significant hint as to their construction than the stellar blaze kindled in the heart of the great Andromeda nebula some undetermined number of years or centuries before its rays reached the earth in the month of August, 1885. The first published discovery was by Dr. Hartwig at Dorpat on August 31; but it was found to have been already seen, on the 19th, by Mr. Isaac W. Ward of Belfast, and on the 17th by M. Ludovic Gully of Rouen. The *negative* observations, on the 16th, of Tempel[1473] and Max Wolf, limited very narrowly the epoch of the apparition. Nevertheless, it did not, like most temporaries, attain its maximum brightness all at once. When first detected, it was of the ninth, by September 1 it had risen to the seventh magnitude, from which it so rapidly fell off that in March it touched the limit of visibility (sixteenth magnitude) with the Washington 26-inch. Its light bleached very perceptibly as it faded.[1474] During the earlier stages of its decline, the contrast was striking between the sharply defined, ruddy disc of the star, and the hazy, greenish-white background upon which it was projected,[1475] and with which it was inevitably suggested to be in some sort of physical connection.

Let us consider what evidence was really available on this point. To begin with, the position of the star was not exactly central. It lay sixteen seconds of arc to the south-west of the true nebular nucleus. Its appearance did not then signify a sudden advance of the nebula towards condensation, nor was it attended by any visible change in it save the transient effect of partial effacement through superior brightness.

Equally indecisive information was derived from the spectroscope. To Vogel, Hasselberg, and Young, the light of the "Nova" seemed perfectly continuous; but Huggins caught traces of bright lines on September 2, confirmed on the 9th;[1476] and Copeland succeeded, on September 30, in measuring three bright bands with an acute-angled prism specially constructed for the purpose.[1477] A shimmer of F was suspected, and had also been perceived by Mr. O. T. Sherman of Yale College. Still, the effect was widely different from that of the characteristic blazing spectrum of a temporary star, and prompted the surmise that here, too, a variable might be under scrutiny. The star, however, was certainly so far "new" that its rays, until their sudden accession of strength, were too feeble to affect even our reinforced senses. Not one of the 1,283 small stars recorded in charts of the nebula could be identified with it; and a photograph taken by Dr. Common, August 16, 1884, on which a multitude of stars down to the fifteenth magnitude had imprinted themselves, showed the uniform, soft gradation of nebulous light to be absolutely unbroken by a stellar indication in the spot reserved for the future occupation of the "Nova."[1478]

So far, then, the view that its relation to the nebula was a merely optical one might be justified; but it became altogether untenable when it was found that what was taken to be a chance coincidence had repeated itself within living memory. On the 21st of May, 1860, M. Auwers perceived at Königsberg a seventh magnitude star shining close to the centre of a nebula in Scorpio, numbered 80 in Messier's Catalogue.[1479] Three days earlier it certainly was not there, and three weeks later it had vanished. The effect to Mr. Pogson (who independently discovered the change, May 28)[1480] was as if the nebula had been *replaced* by a star, so entirely were its dim rays overpowered by the concentrated blaze in their midst. Now, it is simply incredible that two outbursts of so uncommon a character should have *accidentally* occurred just on the line of sight between us and the central portions of two nebulæ; we must, then, conclude that they showed *on* these objects because they took place *in* them. The most favoured explanation is that they were what might be called effects of overcrowding—that some of the numerous small bodies, presumably composing the nebulæ, jostled together, in their intricate circlings, and obtained compensation in heat for their sacrifice of motion. But this is scarcely more than a plausible makeshift of perplexed thought. Mr. W. H. S. Monck, on the other hand, has suggested that new stars appear when dark bodies are rendered luminous by rushing through the gaseous fields of space,[1481] just as meteors kindle in our atmosphere. The idea, which has been revived and elaborated by Dr. Seeliger of Munich,[1482] is ingenious, but was not designed to apply to our present case. Neither of the objects distinguished by the striking variations just described is of gaseous constitution. That in Scorpio appears under high magnifying powers as a "compressed cluster"; that in Andromeda is perhaps, as Sir J. Herschel suggested, "optically nebulous through the smallness of its constituent stars"[1483]—if stars they deserve to be called.

On the 8th of December, 1891, Dr. Max Wolf took a photograph of the region about χ Aurigæ. No stranger so bright as the eighth magnitude was among the stars depicted upon it. On the 10th, nevertheless, a stellar object of the fifth magnitude, situated a couple of degrees to the north-east of β Tauri and previously unrecorded, where eleventh magnitude stars appeared, imprinted itself upon a Harvard negative. Subsequent photographs taken at the same place showed it to have gained about half a magnitude by the 20th; but the plates were not then examined, and the discovery was left to be modestly appropriated by an amateur, the Rev. Dr. Anderson of Edinburgh, by whom it was announced, February 1, 1892, through the medium of an anonymous postcard, to Dr. Copeland, the Astronomer Royal for Scotland.[1484] By him and others, the engines of modern research were promptly set to work. And to good purpose. Nova Aurigæ was the first star of its kind studied by the universal chemical method. It is the first, accordingly, of which authentic records can be handed down to posterity. They are of a most remarkable character. The spectrum of the new object was photographed at Stonyhurst and South Kensington on February 3; a few days later, at Harvard and Lick in America, at Potsdam and Hérény on the Continent of Europe. But by far the most complete impression was secured, February 22, with an exposure of an hour and three-quarters, by Sir William and Lady Huggins, through whose kindness it is reproduced in Plate V., Fig. 1. The range of bright lines displayed in it is of astonishing vividness and extent. It includes all the hydrogen rays dark in the spectrum of Sirius (separately printed for comparison), besides many others still more refrangible, as yet unidentified. Very significant, too, is the marked character of the great prominence lines H and K. The visual spectrum of the Nova was splendidly effective. A

PLATE V.

Photographic and Visual Spectrum of Nova Aurigæ.

Photographic and Visual Spectrum of Nova Aurigæ."

Fig. 1.—From a Photograph taken by Sir William and Lady Huggins, Feb. 22, 1892.

Fig. 2.—From a Drawing made by Lady Huggins, Feb. 2 to 6, 1892.

quartette of brilliant green rays, two of them due to helium, caught the eye; and they had companions too numerous to be easily counted. The hydrogen lines were broad and bright; C blazed, as Mr. Espin said, "like a danger-signal on a dark night"; the sodium pair were identified at Tulse Hill, and the yellow helium ray was suspected to lurk close beside them. Fig. 2 in the same plate shows the spectrum as it was seen and mapped by Lady Huggins, February 2 to 6, together with the spectra employed to test the nature of the emissions dispersed in it. One striking feature will be at once remarked. It is that of the pairing of bright with dark lines. Both in the visible and the photographic regions this singular peculiarity was unmistakable; and since the two series plainly owned the same chemical origin, their separate visibility implied large displacement. Otherwise they would have been superposed, not juxtaposed. Measurements of the bright rays, accordingly, showed them to be considerably pushed down towards the red, while their dark companions were still more pushed up towards the blue end. Thus the spectrum of Nova Aurigæ, like that of β Lyræ, with which it had many points in common, appeared to be really double. It was supposed to combine the light of two distinct bodies, one, of a gaseous nature, moving rapidly away from the earth, the other, giving a more sunlike spectrum, approaching it with even higher speed. The relative velocity determined at Potsdam for these oppositely flying masses amounted to 550 miles a second.[1485] And this prodigious rate of separation was fully maintained during six weeks! It did not then represent a mere periastral rush-past.[1486] To the bodies exhibiting its effects, and parting company for ever under its stress, it must have belonged, with slight diminution, in perpetuity. The luminous outburst by which they became visible was explained by Sir William Huggins, in a lecture delivered at the Royal Institution, May 13, 1892, on the tidal theory of Klinkerfues and Wilsing. Disturbances and deformations due to the mutual attraction of two bulky globes at a close approach would, he considered, "give rise to enormous eruptions of the hotter matters from within, immensely greater, but similar in kind, to solar eruptions; and accompanied, probably, by large electrical disturbances." The multiple aspect and somewhat variable character of both bright and dark lines were plausibly referred to processes of "reversal," such as are nearly always in progress above sun-spots; but the long duration of the star's suddenly acquired lustre did not easily fit in with the adopted rationale. A direct collision, on the other hand, was out of the question, since there had obviously been little, if any, sacrifice of motion; and the substitution of a nebula for one of the "stars"[1487] compelled recourse to scarcely conceivable modes of action for an explanation of the perplexing peculiarities of the compound spectrum.

An unexpected *dénouement*, however, threw all speculations off the track. The Nova contained most of its brightness, fluctuations notwithstanding, until March 9; after which date it ran swiftly and uniformly down towards what was apprehended to be total extinction. No marked change of spectrum attended its decline. When last examined at Tulse Hill, March 24, all the more essential features of its prismatic light were still faintly recognisable.[1488] The object was steadily sinking on April 26, when a (supposed) final glimpse of it was caught with the Lick 36-inch.[1489] It was then of about the sixteenth magnitude. But on August 17 it had sprung up to the tenth, as Professors Holden, Schaeberle, and Campbell perceived with amazement on turning the same instrument upon its place. And to Professor Barnard it appeared, two nights later, not only revived, but transformed into the nucleus of a planetary nebula, 3′ across.[1490] The reality of this seeming distension, however, at once disputed, was eventually disproved. It unquestionably arose from the imperfect focussing power of the telescope for rays of unusual quality.[1491]

The rekindled Nova was detected in this country by Mr. H. Corder, on whose notification Mr. Espin, on August 21, examined its nearly monochromatic spectrum.[1492] The metamorphosis of Nova Cygni seemed repeated.[1493] The light of the new object, like that of its predecessor, was mainly concentrated in a vivid green band, identified with the chief nebular line by Copeland,[1494] Von Gothard,[1495] and Campbell.[1496] The second nebular line was also represented. Indeed, the last-named observer recognised nearly all the eighteen lines measured by him in the Nova as characteristic of planetary nebulæ.[1497] Of particular interest is the emergence in the star-spectrum photographed by Von Gothard of an ultra-violet line originally discovered at Tulse Hill in the Orion nebula, which is also very strong in the Lyra annular nebula, Obviously, then, the physical constitution of Nova Aurigæ became profoundly modified during the four months of its invisibility. The spectrum of February was or appeared compound; that of August was simple; it could be reasonably associated only with a single light-source. Many of the former brilliant lines, too, had vanished, and been replaced by others, at first inconspicuous or absent. As a result, the solar-prominence type, to which the earlier spectrum had seemed to conform, was completely effaced in the later. The cause of these alterations remains mysterious, yet its effects continue. The chromatic behaviour of the semi-extinct Nova, when scrutinised with great refractors, shows its waning light to be distinctly nebular.[1498] Like nearly all its congeners, the star is situated in the full stream of the Milky Way, and we learn without surprise that micrometrical measures by Burnham and Barnard[1499] failed to elicit from it any sign of parallactic shifting. It is hence certain that the development of light, of which the news reached the earth in December, 1891, must have been on a vast scale, and of ancient date. Nova Aurigæ at its maximum assuredly exceeded the sun many times in brightness; and its conflagration can scarcely have occurred less, and may have occurred much more, than a hundred years ago.

By means of the photographic surveys of the skies, carried on in both hemispheres under Professor Pickering's superintendence, such amazing events have been proved to be of not infrequent occurrence. Within six years five new stars were detected from Draper Memorial, or chart-plates by Mrs Fleming, besides the retrospective discovery of a sixth which had rapidly burnt itself out, eight years previously, in Perseus.[1500] Nova Normæ was the immediate successor of Nova Aurigæ; Nova Carinæ and Nova Centauri lit up in 1895, the latter in a pre-existent nebula; Nova Sagittarii and Nova Aquilæ attained brief maxima in 1898 and 1899 respectively. Now, three out of these five stars reproduced with singular fidelity the spectrum of Nova Aurigæ; they displayed the same brilliant rays shadowed, invariably on their blue sides, by dark ones. Palpably, then, the arrangement was systematic and significant; it could not result merely from the casually directed, opposite velocities of bodies meeting in space. The hypothesis of stellar encounters accordingly fell to the ground, and has been provided with no entire satisfactory substitute. Most speculators now fully recognise that motion-displacements cannot be made to account for the doubled spectra of Novæ, and seek recourse instead to some kind of physical agency for producing the observed effect.[1501] And since this is also visible in certain permanent, though peculiar objects—notably in P Cygni, β Lyræ, and η Carinæ—the acting cause must also evidently be permanent and inherent.

The "new star of the new century"[1502] was a visual discovery. Dr. Anderson duplicated, with added *éclat*, his performance of nine years back. In the early morning of February 22, 1901, he perceived that Algol had a neighbour of nearly its own brightness, which a photograph taken by Mr. Stanley Williams, at Brighton, proved to have risen from below the twelfth magnitude within the preceding 28 hours. And it was still swiftly ascending. On the 23rd, it outshone Capella; for a brief space it took rank as the premier star of the northern hemisphere. A decline set in promptly, but was pursued hesitatingly. The light fluctuated continually over a range of a couple of magnitudes, and with a close approach, during some weeks, to a three-day periodicity. A year after the original outburst, the star was still conspicuous with an opera-glass. The spectrum underwent amazing changes. At first continuous, save for fine dark lines of hydrogen and helium, it unfolded within forty-eight hours a composite range of brilliant and dusky bands disposed in the usual fashion of Novæ. These lasted until far on in March, when hydrogen certainly, and probably other substances as well, ceased to exert any appreciable absorptive action. Blue emissions of the Wolf-Rayet type then became occasionally prominent, in remarkable correspondence with the varying lustre of the star;[1503] finally, a band at λ 3969, found by Wright at Lick to characterise nebular spectra,[1504] assumed abnormal importance; and in July the nebular transformation might be said to be complete. Striking alterations of colour attended these spectral vicissitudes. White to begin with, the star soon turned deep red, and its redness was visibly intensified at each of its recurring minima of light. Blanching, however, ensued upon the development of its nebulous proclivities; and its surviving rays are of a steely hue.

All the more important investigations of Nova Persei were conducted by photographic means. Libraries of spectral plates were collected at the Yerkes and Lick Observatories, at South Kensington, Stonyhurst, and Potsdam, and await the more exhaustive interpretation of the future. Meanwhile, extraordinary revelations have been supplied by immediate photographic delineation. On August 22 and 23, 1901, Professor Max Wolf, by long exposures with the 16-inch Bruce twin objectives of the Königstuhl Observatory (Heidelberg), obtained indications of a large nebula finely ramified, extending south-east of the Nova;[1505] and the entire formation came out in four hours with the Yerkes 2-foot reflector, directed to it by Mr. Ritchey on September 20.[1506] It proved to be a great spiral encircling, and apparently emanating from, the star. But if so, tumultuously, and under stress of catastrophic impulsions. A picture obtained by Mr. Perrine with the Crossley refractor, in 7h. 19m., on November 7 and 8, disclosed the progress of a startling change.[1507] Comparison with the Yerkes photograph showed that during the intervening 48 days four clearly identifiable condensations had become displaced, all to the same extent of about 90 seconds of arc, and in fairly concordant directions, suggesting motion *round* the Nova as well as away from it. The velocity implied, however, is so prodigious as virtually to exclude the supposition of a bodily transport of matter. It should be at the rate of no less than twenty thousand miles a second, admitting the object to be at a distance from us corresponding to an annual parallax of one-tenth of a second, and actual measurements show it to be indefinitely more remote. The fact of rapid variations in the nebula was reaffirmed, though with less precision, from Yerkes photographs of November 9 and 13, Mr. Ritchey inferring a general expansion of its southern portions.[1508] Much further evidence must be at hand before a sane judgment can be formed as to the nature of the strange events taking place in that secluded corner of the Galaxy.[1509] And it is highly probable that the illumination of the nebulous wreaths round the star will prove no less evanescent than the blazing of the star itself.

We have been compelled somewhat to anticipate our narrative as regards inquiries into the nature of nebulæ. The excursions of opinion on the point were abruptly restricted and defined by the application to them of the spectroscope. On August 29, 1864, Sir William Huggins sifted through his prisms the rays of a bright planetary nebula in Draco.[1510] To his infinite surprise, they proved to be mainly of one colour. In other words, they avowed their origin from a mass of glowing vapour. As to what *kind* of vapour it might be by which Herschel's conjecture of a "shining fluid" diffused at large throughout the cosmos was thus unexpectedly verified, an answer only partially satisfactory could be afforded. The conspicuous bright line of the Draco nebula seemed to agree in position with one emitted by nitrogen, but has since proved to be distinct from it; of its two fainter companions, one was unmistakably the F line of hydrogen, while the other, in position intermediate between the two, still remains unidentified.

By 1868 Huggins had satisfactorily examined the spectra of about seventy nebulæ, of which one-third displayed a gaseous character.[1511] All of these gave the green ray fundamental to the nebular spectrum, and emanating from an unknown form of matter named by Sir William Huggins "nebulum." It is associated with seven or eight hydrogen lines, with three of "yellow" helium, and with a good many of undetermined origin. The absence of the crimson radiation of hydrogen—perceived with difficulty only in some highly condensed objects—is an anomaly very imperfectly explained as a physiological effect connected with the extreme faintness of nebular light.[1512] An approximate coincidence between the chief nebular line and a "fluting" of magnesium having been alleged by Lockyer in support of his meteoritic hypothesis of nebular constitution, it became of interest to ascertain its reality. The task was accomplished by Sir William and Lady Huggins in 1889 and 1890,[1513] and by Professor Keeler, with the advantages of the Mount Hamilton apparatus and atmosphere, in 1890-91.[1514] The upshot was to show a slight but sure discrepancy as to place, and a marked diversity as to character, between the two qualities of light. The nebular ray (wave-length 5,007 millionths of a millimetre) is slightly more refrangible than the magnesium fluting-edge, and it is sharp and fine, with no trace of the unilateral haze necessarily clinging even to the last “remnant” of a banded formation.

Planetary and annular nebulæ are, without exception, gaseous, as well as those termed “irregular,” which frequent the region of the Milky Way. Their constitution usually betrays itself to the eye by their blue or greenish colour; while those yielding a continuous spectrum are of a dull white. Among the more remarkable of these are the well-known nebula in Andromeda, and the great spiral in Canes Venatici; and, as a general rule, the emissions of all such nebulæ as present the appearance of star-clusters grown misty through excessive distance are of the same kind. It would, however, be eminently rash to conclude thence that they are really aggregations of sun-like bodies. The improbability of such an inference has been greatly enhanced by the occurrence, at an interval of a quarter of a century, of stellar outbursts in the midst of two of them. For it is practically certain that the temporary stars were equally remote with the hazy formations they illuminated; hence, if the constituent particles of the latter be suns, the incomparably vaster orbs by which their feeble light was well-nigh obliterated must, as was argued by Mr. Proctor, have been on a scale of magnitude such as the imagination recoils from contemplating. Nevertheless, Dr. Scheiner, not without much difficulty, obtained, in January, 1899, spectrographic prints of the Andromeda nebula, indicative, he thought, of its being a cluster of solar stars.[1515] Sir William and Lady Huggins, on the other hand, *saw*, in 1897, bright intermixed with dark bands in the spectrum of the same object.[1516] And Mr. Maunder conjectures all “white” nebulæ to be made up of sunlets in which the coronal element predominates, while chromospheric materials assert their presence in nebulæ of the “green” variety.[1517]

Among the ascertained analogies between the stellar and nebular systems is that of variability of light. On October 11, 1852, Mr. Hind discovered a small nebula in Taurus. Chacornac observed it at Marseilles in 1854, but was confounded four years later to find it vanished. D’Arrest missed it October 3, and redetected it December 29, 1861. It was easily seen in 1865-66, but invisible in the most powerful instruments from 1877 to 1880.[1518] Barnard, however, made out an almost evanescent trace of it, October 15, 1890, with the great Lick telescope,[1519] and saw it easily in the spring of 1895, while six months later it evaded his most diligent search.[1520] Then again, on September 28, 1897, the Yerkes 40-inch disclosed it to him as a mere shimmer at the last limit of visibility; and it came out in three diffuse patches on plates to which, on December 6 and 27, 1899, Keeler gave prolonged exposures with the Crossley reflector.[1521] Moreover, a fairly bright adjacent nebula, perceived by O. Struve in 1868, and observed shortly afterwards by d’Arrest, has totally vanished, and was most likely only a temporary apparition. These are the most authentic instances of nebular variability. Many others have been more or less plausibly alleged;[1522] but Professor Holden’s persuasion, acquired from an exhaustive study of the records since 1758,[1523] that the various parts of the Orion nebula fluctuate continually in relative lustre, has not been ratified by photographic evidence.

The case of the "trifid" nebula in Sagittarius, investigated by Holden in 1877,[1524] is less easily disposed of. What is certain is that a remarkable triple star, centrally situated, according to the observations of both the Herschels, 1784-1833, in a dark space between the three great *lobes* of the nebula, is now, and has been since 1839, densely involved in one of them; and since the hypothesis of relative motion is on many grounds inadmissible, the change that has apparently taken place must be in the distribution of light. One no less conspicuous was adduced by Mr. H. C. Russell, director of the Sydney Observatory.[1525] A particularly bright part of the great Argo nebula, as drawn by Sir John Herschel, has, it would seem, almost totally disappeared. He noticed its absence in 1871, using a 7-inch telescope, failed equally later on to find it with an 11-1/2-inch, and his long-exposure photographs show no vestige of it. The same structure is missing from, or scarcely traceable in, a splendid picture of the nebula taken by Sir David Gill in twelve hours distributed over four nights in March, 1892.[1526] An immense gaseous expanse has, it would seem, sunk out of sight. Materially it is no doubt there; but the radiance has left it.

Nebulæ have no ascertained proper motions. No genuine change of place in the heavens has yet been recorded for any one of them. All equally hold aloof, so far as telescopic observation shows, from the busy journeyings of the stars. This seeming immobility is partly an effect of vast distance. Nebular parallax has, up to the present, proved evanescent, and nebular parallactic drift, in response to the sun's advance through space, remains likewise imperceptible.[1527] It may hence be presumed that no nebulæ occur within the sphere occupied by the nearer stars. But the difficulty of accurately measuring such objects must also be taken into account. Displacements which would be conspicuous in stars might easily escape detection in ill-defined, hazy masses. Thus the measures executed by d'Arrest in 1857[1528] have not yet proved effective for their designed purpose of contributing to the future detection of proper motions. Some determinations made by Mr. Burnham with the Lick refractor in 1891,[1529] will ultimately afford a more critical test. He found that nearly all planetary nebulæ include a sharp stellar nucleus, the position of which with reference to neighbouring stars could be fixed no less precisely than if it were devoid of nebulous surroundings. Hence, the objects located by him cannot henceforward shift, were it only to the extent of a small fraction of a second, without the fact coming to the knowledge of astronomers.

The spectroscope, however, here as elsewhere, can supplement the telescope; and what it has to tell, it tells at once, without the necessity of waiting on time to ripen results. Sir William Huggins made, in 1874,[1530] the earliest experiments on the radial movements of nebulæ. But with only a negative upshot. None of the six objects examined gave signs of spectral alteration, and it was estimated that they must have done so had they been in course of recession from or approach towards the earth by as much as twenty-five miles a second. With far more powerful appliances, Professor Keeler renewed the attempt at Lick in 1890-91. His success was unequivocal. Ten planetary nebulæ yielded perfectly satisfactory evidence of line-of-sight motion,[1531] the swiftest traveller being the well-known greenish globe in Draco,[1532] found to be hurrying towards the earth at the rate of forty miles a second. For the Orion nebula, a recession of about eleven miles was determined,[1533] the whole of which may, however, very well belong to the solar system itself, which, by its translation towards the constellation Lyra, is certainly leaving the great nebula pretty rapidly behind. The anomaly of seeming nebular fixity has nevertheless been removed; and the problem of nebular motion has begun to be solved through the demonstrated possibility of its spectroscopic investigation.

Keeler's were the first trustworthy determinations of radial motion obtained visually. That the similar work on the stars begun at Greenwich in 1874, and carried on for thirteen years, remained comparatively unfruitful, was only what might have been expected, the instruments available there being altogether inadequate for the attainment of a high degree of accuracy.

The various obstacles in the way of securing it were overcome by the substitution of the sensitive plate for the eye. Air-tremors are thus rendered comparatively innocuous; and measurements of stellar lines displaced by motion with reference to fiducial lines from terrestrial sources, photographed on the same plates, can be depended upon within vastly reduced limits of error. Studies for the realisation of the "spectrographic" method were begun by Dr. Vogel and his able assistant, Dr. Scheiner, at Potsdam in 1887. Their preliminary results, communicated to the Berlin Academy of Sciences, March 15, 1888, already showed that the requirements for effective research in this important branch were at last about to be complied with. An improved instrument was erected in the autumn of the same year, and the fifty-one stars, bright enough for determination with a refractor of 11 inches aperture, were promptly taken in hand. A list of their motions in the line of sight, published in 1892,[1534] was of high value, both in itself and for what it promised. One noteworthy inference from the data it collected was that the eye tends, under unfavourable circumstances, to exaggerate the line-displacements it attempts to estimate. The velocities photographically arrived at were of much smaller amounts than those visually assigned. The average speed of the Potsdam stars came out only 10·4 miles a second, the quickest among them being Aldebaran, with a recession of thirty miles a second. More lately, however, Deslandres and Campbell have determined for ζ Herculis and η Cephei respectively approaching rates of forty-four and fifty-four miles a second.

The installation, in 1900, of a photographic refractor 31-1/2 inches in aperture, coupled with a 20-inch guiding telescope, will enable Dr. Vogel to investigate spectrographically some hundreds of stars fainter than the second magnitude; and the materials thus accumulated should largely help to provide means for a definite and complete solution of the more than secular problem of the sun's advance through space. The solution should be complete, because including a genuine determination of the sun's velocity, apart from assumptions of any kind. M. Homann's attempt, in 1885,[1535] to extract some provisional information on the subject from the radial movements of visually determined stars gave a fair earnest of what might be done with materials of a better quality. He arrived at a goal for the sun's way shifted eastward to the constellation Cygnus—a result congruous with the marked tendency of recently determined apexes to collect in or near Lyra; and the most probable corresponding velocity seemed to be about nineteen miles a second, or just that of the earth in its orbit. A more elaborate investigation of the same kind, based by Professor Campbell in 1900[1536] upon the motions of 280 stars, determined with extreme precision, suffered in completeness through lack of available data from the southern hemisphere. The outcome, accordingly, was an apex most likely correctly placed as regards right ascension, but displaced southward by some fifteen degrees. The speed of twelve miles a second, assigned to the solar translation, approximates doubtless very closely to the truth.

A successful beginning was made in nebular spectrography by Sir William Huggins, March 7, 1882.[1537] Five lines in all stamped themselves upon the plate during forty-five minutes of exposure to the rays of the strange object in Orion. Of these, four were the known visible lines, and a fifth, high up in the ultra-violet, at wave-length 3,727, has evidently peculiar relationships, as yet imperfectly apprehended. It is strong in the spectra of many planetaries; it helped to characterise the nebular metamorphosis of Nova Aurigæ, yet failed to appear in Nova Persei. Two additional hydrogen lines, making six in all, were photographed at Tulse Hill, from the Orion nebula, in 1890;[1538] and Dr. Copeland's detection in 1886[1539] of the yellow ray D_3 gave the first hint of the presence of helium in this prodigious formation. Nor are there wanting spectroscopic indications of its physical connection with the stars visually involved in it. Sir William and Lady Huggins found a plate exposed February 5, 1888, impressed with four groups of fine bright lines, originating in the continuous light of two of the trapezium-stars, but extending some way into the surrounding nebula.[1540] And Dr. Scheiner[1541] argued a wider relationship from the common possession, by the nebula and the chief stars in the constellation Orion, of a blue line, bright in the one case, dark in the others, since identified as a member of one of the helium series.

The structural unity of the stellar and nebular orders in this extensive region of the sky has also, by direct photographic means, been unmistakably affirmed.

The first promising autographic picture of the Orion nebula was obtained by Draper, September 30, 1880.[1542] The marked approach towards a still more perfectly satisfactory result shown by his plates of March, 1881 and 1882, was unhappily cut short by his death. Meanwhile, M. Janssen was at work in the same field from 1881, with his accustomed success.[1543] But Dr. A. Ainslie Common left all competitors far behind with a splendid picture, taken January 30, 1883, by means of an exposure of thirty-seven minutes in the focus of his 3-foot silver-on-glass mirror.[1544] Photography may thereby be said to have definitely assumed the office of historiographer to the nebulæ, since this one impression embodies a mass of facts hardly to be compassed by months of labour with the pencil, and affords a record of shape and relative brightness in the various parts of the stupendous object it delineates which must prove invaluable to the students of its future condition. Its beauty and merit were officially recognised by the award of the Astronomical Society's Gold Medal in 1884.

A second picture of equal merit, obtained by the same means, February 28, 1883, with an exposure of one hour, is reproduced in the frontispiece. The vignette includes two specimens of planetary photography. The Jupiter, with the great red spot conspicuous in the southern hemisphere, is by Dr. Common. It dates from September 3, 1879, and was accordingly one of the earliest results with his 36-inch, the direct image in which imprinted itself in a fraction of a second, and was subsequently enlarged on paper about twelve times. The exquisite little picture of Saturn was taken at Paris by MM. Paul and Prosper Henry, December 21, 1885, with their 13-inch photographic refractor. The telescopic image was in this case magnified eleven times previous to being photographed, an exposure of about five seconds being allowed; and the total enlargement, as it now appears, is nineteen times. A trace of the dusky ring perceptible on the original negative is lost in the print.

A photograph of the Orion nebula taken by Dr. Roberts in 67 minutes, November 30, 1886, made a striking disclosure of the extent of that prodigious object. More than six times the nebulous area depicted on Dr. Common's plates is covered by it, and it plainly shows an adjacent nebula, separately catalogued by Messier, to belong to the same vast formation.

This disposition to annex and appropriate has come out more strongly with every increase of photographic power. Plates exposed at Harvard College in March, 1888, with an 8-inch portrait-lens (the same used in the preparation of the Draper Catalogue) showed the old-established "Fish-mouth" nebula not only to involve the stars of the sword-handle, but to be in tolerably evident connection with the most easterly of the three belt-stars, from which a remarkable nebulous appendage was found to proceed.[1545] A still more curious discovery was made by W. H. Pickering in 1889.[1546] Photographs taken in three hours from the summit of Wilson's Peak in California revealed the existence of an enormous, though faint spiral structure, enclosing in its span of nearly seventeen degrees the entire stellar and nebulous group of the Belt and Sword, from which it most likely, although not quite traceably, issues as if from a nucleus. A startling glimpse is thus afforded of the cosmical importance of that strange "hiatus" in the heavens which excited the wonder of Huygens in 1656. The inconceivable attenuation of the gaseous stuff composing it was virtually demonstrated by Mr. Ranyard.[1547]

In March, 1885, Sir Howard Grubb mounted for Dr. Isaac Roberts, at Maghull, near Liverpool (his observatory has since been transferred to Crowborough in Sussex), a silver-on-glass reflector of twenty inches aperture, constructed expressly for use in celestial photography. A series of nebula-pictures, obtained with this fine instrument, have proved highly instructive both as to the structure and extent of these wonderful objects; above all, one of the great Andromeda nebula, to which an exposure of three hours was given on October 1, 1888.[1548] In it a convoluted structure replaced and rendered intelligible the anomalously rifted mass seen by Bond in 1847.[1549] The effects of annular condensation appeared to have stamped themselves upon the plate, and two attendant nebulæ presented the aspect of satellites already separated from the parent body, and presumably revolving round it. The ring-nebula in Lyra was photographed at Paris in 1886, and shortly afterwards by Von Gothard with a 10-inch reflector,[1550] and he similarly depicted in 1888 the two chief spiral and other nebulæ.[1551] Photographs of the Lyra nebula taken at Algiers in 1890,[1552] and at the Vatican observatory in 1892,[1553] were remarkable for the strong development of a central star, difficult of telescopic discernment, but evidently of primary importance to the annular structure around.

The uses of photography in celestial investigations become every year more manifold and more apparent. The earliest chemical star-pictures were those of Castor and Vega, obtained with the Cambridge refractor in 1850 by Whipple of Boston under the direction of W. C. Bond. Double-star photography was inaugurated under the auspices of G. P. Bond, April 27, 1857, with an impression, obtained in eight seconds, of Mizar, the middle star in the handle of the Plough. A series of measures from sixty-two similar images gave the distance and position-angle of its companion with about the same accuracy attainable by ordinary micrometrical operations; and the method and upshot of these novel experiments were described in three papers remarkably forecasting the purposes to be served by stellar photography.[1554] The matter next fell into the able hands of Rutherfurd, who completed in 1864 a fine object glass (of 11-1/2 inches) corrected for the ultra-violet rays, consequently useless for visual purposes. The sacrifice was recompensed by conspicuous success. A set of measurements from his photographs of nearly fifty stars in the Pleiades, and their comparison with Bessel's places, enabled Dr. Gould to announce, in 1866, that during the intervening third of a century no changes of importance had occurred in their relative positions.[1555] And Mr. Harold Jacoby[1556] similarly ascertained the fixity of seventy-five of Rutherfurd's Atlantids, between the epoch 1873 and that of Dr. Elkin's heliometric triangulation of the cluster in 1886,[1557] extending the interval to twenty-seven years by subsequent comparisons with plates taken at Lick, September 27, 1900.[1558] Positive, however, as well as negative results have ensued from the application of modern methods to that antique group.

On October 19, 1859, Wilhelm Tempel, a Saxon peasant by origin, later a skilled engraver, discovered with a small telescope, bought out of his scanty savings, an elliptical nebulosity, stretching far to the southward from the star Merope. It attracted the attention of many observers, but was so often missed, owing to its extreme susceptibility to adverse atmospheric influences, as to rouse unfounded suspicions of its variability. The detection of this evasive object gave a hint, barely intelligible at the time, of further revelations of the same kind by more cogent means.

A splendid photograph of 1,421 stars in the Pleiades, taken by the MM. Henry with three hours' exposure, November 16, 1885, showed one of the brightest of them to have a small spiral nebula, somewhat resembling a strongly-curved comet's tail, attached to it. The reappearance of this strange appurtenance on three subsequent plates left no doubt of its real existence, visually attested at Pulkowa, February 5, 1886, by one of the first observations made with the 30-inch equatoreal.[1559] Much smaller apertures, however, sufficed to disclose the "Maia nebula," *once it was known to be there*. Not only did it appear greatly extended in the Vienna 27-inch,[1560] but MM. Perrotin and Thollon saw it with the Nice 15-inch, and M. Kammermann of Geneva, employing special precautions, with a refractor of only ten inches aperture.[1561] The advantage derived by him for bringing it into view, from the insertion into the eye-piece of a uranium film, gives, with its photographic intensity, valid proof that a large proportion of the light of this remarkable object is of the ultra-violet kind.

The beginning thus made was quickly followed up. A picture of the Pleiades procured at Maghull in eighty-nine minutes, October 23, 1886, revealed nebulous surroundings to no less than four leading stars of the group, namely, Alcyone, Electra, Merope, and Maia; and a second impression, taken in three hours on the following night, showed further "that the nebulosity extends in streamers and fleecy masses till it seems almost to fill the spaces between the stars, and to extend far beyond them."[1562] The coherence of the entire mixed structure was, moreover, placed beyond doubt by the visibly close relationship of the stars to the nebulous formations surrounding them in Dr. Roberts's striking pictures. Thus Goldschmidt's notion that all the clustered Pleiades constitute, as it were, a second Orion trapezium in the midst of a huge formation of which Tempel's nebula is but a fragment,[1563] has been to some extent verified. Yet it seemed fantastic enough in 1863.

Then in 1888 the MM. Henry gave exposures of four hours each to several plates, which exhibited on development some new features of the entangled nebulæ. The most curious of these was the linking together of stars by nebulous chains. In one case seven aligned stars appeared strung on a silvery filament, "like beads on a rosary."[1564] The "rows of stars," so often noticed in the sky, may, then, be concluded to have more than an imaginary existence. Of the 2,326 stars recorded in these pictures, a couple of hundred among the brightest can, at the outside, be reckoned as genuine Pleiades. The great majority were relegated, by Pickering's[1565] and Stratonoff's[1566] counts of the stellar populace *in* and *near* the cluster, to the position of outsiders from it. They are undistinguished denizens of the abysmal background upon which it is projected.

Investigations of its condition were carried a stage further by Barnard. On November 14, 1890,[1567] he discovered visually with the Lick refractor a close nebulous satellite to Merope, photographs of which were obtained by Keeler in 1898.[1568] It appears in them of a rudely pentagonal shape, a prominent angle being directed towards the adjacent star. Finally, an exposure of ten hours made by Barnard with the Willard lens indicated the singular fact that the entire group is embedded in a nebulous matrix, streaky outliers of which blur a wide surface of the celestial vault.[1569] The artist's conviction of the reality of what his picture showed was confirmed by negatives obtained by Bailey at Arequipa in 1897, and by H. C. Wilson at Northfield (Minnesota) in 1898.[1570]

With the Ealing 3-foot reflector, sold by Dr. Common to Mr. Crossley, and by him presented to the Lick Observatory, Professor Keeler took in 1899 a series of beautiful and instructive nebula[1571] photographs; One of the Trifid may be singled out as of particular excellence. An astonishing multitude of new nebulæ were revealed by trial-exposures with this instrument. A "conservative estimate" gave 120,000 as the number coming within its scope. Moreover, the majority of those actually recorded were of an unmistakable spiral character, and they included most of Sir John Herschel's "double nebulæ," previously supposed to exemplify the primitive history of binary stellar systems.[1572] Dr. Max Wolf's explorations with a 6-inch Voigtländer lens in 1901 emphatically reaffirmed the inexhaustible wealth of the nebular heavens. In one restricted region, midway between Præsepe and the Milky Way, he located 135 nebulæ, where only three had until then been catalogued; and he counted 108 such objects clustering round the star 31 Comæ Berenices,[1573] and so closely that all might be occulted together by the moon. The general photographic Catalogue of Nebulæ which Dr. Wolf has begun to prepare[1574] will thus be a most voluminous work.

The history of celestial photography at the Cape of Good Hope began with the appearance of the great comet of 1882. No special apparatus was at hand; so Sir David Gill called in the services of a local artist, Mr. Allis of Mowbray, with whose camera, strapped to the Observatory equatoreal, pictures of conspicuous merit were obtained. But their particular distinction lay in the multitude of stars begemming the background. (See Plate III.) The sight of them at once opened to the Royal Astronomer a new prospect. He had already formed the project of extending Argelander's "Durchmusterung" from the point where it was left by Schönfeld to the southern pole; and his ideas regarding the means of carrying it into execution crystallised at the needle touch of the cometary experiments. He resolved to employ photography for the purpose. The exposure of plates was accordingly begun, under the care of Mr. Ray Woods, in 1885; and in less than six years, the sky, from 19° of south latitude to the pole, had been covered in duplicate. Their measurement, and the preparation of a catalogue of the stars imprinted upon them, were generously undertaken by Professor Kapteyn, and his laborious task has at length been successfully completed. The publication, in 1900, of the third and concluding volume of the "Cape Photographic Durchmusterung"[1575] placed at the disposal of astronomers a photographic census of the heavens fuller and surer than the corresponding visual enumeration executed at Bonn. It includes 454,875 stars, nearly to the tenth magnitude, and their positions are reliable to about one second of arc.

The production of this important work was thus a result of the Cape comet-pictures; yet not the most momentous one. They turned the scale in favour of recourse to the camera when the MM. Henry encountered, in their continuation of Chacornac's half-finished enterprise of ecliptical charting, sections of the Milky Way defying the enumerating efforts of eye and hand. The perfect success of some preliminary experiments made with an instrument constructed by them expressly for the purpose was announced to the Academy of Sciences at Paris, May 2, 1885. By its means stars estimated as of the sixteenth magnitude clearly recorded their presence and their places; and the enormous increase of knowledge involved may be judged of from the fact that, in a space of the Milky Way in Cygnus 2° 15′ by 3°, where 170 stars had been mapped by the old laborious method, about five thousand stamped their images on a single Henry plate.

These results suggested the grand undertaking of a general photographic survey of the heavens, and Gill's proposal, June 4, 1886, of an International Congress for the purpose of setting it on foot was received with acclamation, and promptly acted upon. Fifty-six delegates of seventeen different nationalities met in Paris, April 16, 1887, under the presidentship of Admiral Mouchez, to discuss measures and organise action. They resolved upon the construction of a Photographic Chart of the whole heavens, comprising stars of a fourteenth magnitude, to the surmised number of twenty millions; to be supplemented by a Catalogue, framed from plates of comparatively short exposure, giving start to the eleventh magnitude. These will probably amount to about one million and a quarter. For procuring both sets of plates, instruments were constructed precisely similar to that of the MM. Henry, which is a photographic refractor, thirteen inches in aperture, and eleven feet focus, attached to a guiding telescope of eleven inches aperture, corrected, of course, for the visual rays. Each place covers an area of four square degrees, and since the series must be duplicated to prevent mistakes, about 22,000 plates will be needed for the Chart alone. The task of preparing them was apportioned among eighteen observatories scattered over the globe, from Mexico to Melbourne; but three in South America having become disabled or inert, were replaced in 1900 by those at Cordoba, Montevideo, and Perth, Western Australia. Meanwhile, the publication of results has begun, and is likely to continue for at least a quarter of a century. The first volume of measures from the Potsdam Catalogue-plates was issued in 1899, and its successors, if on the same scale, must number nearly 400. Moreover, ninety-six heliogravure enlargements from the Paris Chart-plates, distributed in the same year, supplied a basis for the calculation that the entire Atlas of the sky, composed of similar sheets, will form a pile thirty feet high and two tons in weight![1576] It will, however, possess an incalculable scientific value. For millions of stars can be determined by its means, from their imprinted images, with an accuracy comparable to that attainable by direct meridian observations.

One of the most ardent promoters of the scheme it may be expected to realise was Admiral Mouchez, the successor of Leverrier in the direction of the Paris Observatory. But it was not granted to him to see the fruition of his efforts. He died suddenly June 25, 1892.[1577] Although not an astronomer by profession, he had been singularly successful in pushing forward the cause of the science he loved, while his genial and open nature won for him wide personal regard. He was replaced by M. Tisserand, whose mathematical eminence fitted him to continue the traditions of Delaunay and Leverrier. But his career, too, was unhappily cut short by an unforeseen death on October 20, 1896; and the more eminent among the many qualifications of his successor, M. Maurice Loewy, are of the practical kind.

The sublime problem of the construction of the heavens has not been neglected amid the multiplicity of tasks imposed upon the cultivators of astronomy by its rapid development. But data of a far higher order of precision, and indefinitely greater in amount, than those at the disposal of Herschel or Struve must be accumulated before any definite conclusions on the subject are possible. The first organised effort towards realising this desideratum was made by the German Astronomical Society in 1865, two years after its foundation at Heidelberg. The original programme consisted in the *exact* determination of the places of all Argelander's stars to the ninth magnitude (exclusive of the polar zone), from the reobservation of which, say, in the year 1950, astronomers of two generations hence may gather a vast store of knowledge—directly of the apparent motions, indirectly of the mutual relations binding together the suns and systems of space. Thirteen observatories in Europe and America joined in the work, now virtually terminated. Its scope was, after its inception, widened to include southern zones as far as the Tropic of Capricorn; this having been rendered feasible by Schönfeld's extension (1875-1885) of Argelander's survey. Thirty thousand additional stars thus taken in were allotted in zones to five observatories. Another important undertaking of the same class is the reobservation of the 47,300 stars in Lalande's *Histoire Céleste*. Begun under Arago in 1855, its upshot has been the publication of the great Paris Catalogue, issued in eight volumes, between 1887 and 1902. From a careful study of their secular changes in position, M. Bossert has already derived the proper motions of a couple of thousand out of nearly fifty thousand stars enumerated in it.

Through Dr. Gould's unceasing labours during his fifteen years' residence at Cordoba, a detailed acquaintance with southern stars was brought about. His *Uranometria Argentina* (1879) enumerates the magnitudes of 8,198 out of 10,649 stars visible to the naked eye under those transparent skies; 33,160 down to 9-1/2 magnitude are embraced in his "zones"; and the Argentine General Catalogue of 32,468 southern stars was published in 1886. Valuable work of the same kind has been done at the Leander McCormick Observatory, Virginia, by Professor O. Stone; while the late Redcliffe observer's "Cape Catalogue for 1880′ affords inestimable aid to the practical astronomer south of the line, which has been reinforced with several publications issued by the present Astronomer Royal at the Cape. Moreover, the gigantic task entered upon in 1860 by Dr. C. H. F. Peters, director of the Litchfield Observatory, Clinton (N.Y.), and of which a large instalment was finished in 1882, deserves honourable mention. It was nothing less than to map all stars down to, and even below, the fourteenth magnitude, situated within 30° on either side of the ecliptic, and so to afford “a sure basis for drawing conclusions with respect to the changes going on in the starry heavens.”[1578]

It is tolerably safe to predict that no work of its kind and for its purpose will ever again be undertaken. In a small part of one night stars can now be got to register themselves more numerously and more accurately than by the eye and hand of the most skilled observer in the course of a year. Fundamental catalogues, constructed by the old, time-honoured method, will continue to furnish indispensable starting-points for measurement; and one of especial excellence was published by Professor Newcomb in 1899;[1579] but the relative places of the small crowded stars—the sidereal οι‘ πο′λλοι—will henceforth be derived from their autographic statements on the sensitive plate. Even the secondary purpose—that of asteroidal discovery—served by detailed stellar enumeration, is more surely attained by photography than by laborious visual comparison. For planetary movement betrays itself in a comparatively short time by turning the imprinted image of the object affected by it from a dot into a trail.

In the arduous matter of determining star distances progress has been steady, and bids fair to become rapidly accelerated. Together, yet independently, Gill and Elkin carried out, at the Cape Observatory in 1882-83, an investigation of remarkable accuracy into the parallaxes of nine southern stars. One of these was the famous α Centauri, the distance of which from the earth was ascertained to be just one-third greater than Henderson had made it. The parallax of Sirius, on the other hand, was doubled, or its distance halved; while Canopus proved to be quite immeasurably remote—a circumstance which, considering that, among all the stellar multitude, it is outshone only by the radiant Dog-star, gives a stupendous idea of its real splendour and dimensions.

Inquiries of this kind were, for some years, successfully pursued at the observatory of Dunsink, near Dublin. Annual perspective displacements were by Dr. Brünnow detected in several stars, and in others remeasured with a care which inspired just confidence. His parallax for α Lyræ (0·13′) was authentic, though slightly too large (Elkin’s final results gave π = 0·082′); and the received value for the parallax of the swiftly travelling star “Groombridge 1,830′ scarcely differs from that arrived at by him in 1871 (π = 0·09′). His successor as Astronomer-Royal for Ireland, Sir Robert Stawell Ball (now Lowndean Professor of Astronomy in the University of Cambridge), has done good service in the same department. For besides verifying approximately Struve’s parallax of half a second of arc for 61 Cygni, he refuted, in 1811, by a sweeping search for (so-called) “large” parallaxes, certain baseless conjectures of comparative nearness to the earth, in the case of red and temporary stars.[1580] Of 450 objects thus cursorily examined, only one star of the seventh magnitude, numbered 1,618 in Groombridge’s Circumpolar Catalogue, gave signs of measurable vicinity. Similarly, a reconnaissance among rapidly moving stars lately made by Dr. Chase with the Yale heliometer[1581] yielded no really large, and only eight appreciable parallaxes among the 92 subjects of his experiments.

A second campaign in stellar parallax was undertaken by Gill and Elkin in 1887. But this time the two observers were in opposite hemispheres. Both used heliometers. Dr. Elkin had charge of the fine instrument then recently erected in Yale College Observatory; Sir David Gill employed one of seven inches, just constructed under his directions, in first-rate style, by the Repsolds of Hamburg. Dr. Elkin completed in 1888 his share of the more immediate joint programme, which consisted in the determination, by direct measurement, of the average parallax of stars of the first magnitude. It came out, for the ten northern luminaries, after several revisions, 0·098′, equivalent to a light-journey of thirty-three years. The deviations from this average were, indeed, exceedingly wide. Two of the stars, Betelgeux and α Cygni, gave no certain sign of any perspective shifting; of the rest, Procyon, with a parallax of 0·334′, proved the nearest to our system. At the mean distance concluded for these ten brilliant stars, the sun would show as of only fifth magnitude; hence it claims a very subordinate rank among the suns of space. Sir David Gill's definitive results were published in 1900.[1582] As the average parallax of the eleven brightest stars in the southern hemisphere, they gave 0·13′, a value enhanced by the exceptional proximity of α Centauri. Yet four of these conspicuous objects—Canopus, Rigel, Spica, and β Crucis—gave no sign of perspective response to the annual change in our point of view. The list included eleven fainter stars with notable proper motions, and most of these proved to have fairly large parallaxes. Among other valuable contributions to this difficult branch may be instanced Bruno Peter's measurements of eleven stars with the Leipzig heliometer, 1887-92;[1583] Kapteyn's application of the method by differences in right ascension to fifteen stars observed on the meridian 1885-89;[1584] and Flint's more recent similar determinations at Madison, Wisconsin.[1585]

The great merit of having rendered photography available for the sounding of the celestial depths belongs to Professor Pritchard. The subject of his initial experiment was 61 Cygni. From measurements of 200 negatives taken in 1886, he derived for that classic star a parallax of 0·438′, in satisfactory agreement with Ball's of 0·468′. A detailed examination convinced the Astronomer-Royal of its superior accuracy to Bessel's result with the heliometer. The Savilian Professor carried out his project of determining all second magnitude stars to the number of about thirty,[1586] conveniently observable at Oxford, obtaining as the general outcome of the research an average parallax of 0·056′, for objects of that rank. But this value, though in itself probable, cannot be accepted as authoritative, in view of certain inaccuracies in the work adverted to by Jacoby,[1587] Hermann Davis, and Gill. The method has, nevertheless, very large capabilities. Professor Kapteyn showed, in 1889,[1588] the practicability of deriving parallaxes wholesale from plates exposed at due intervals, and applied his system, in 1900, with encouraging success, to a group of 248 stars.[1589] The apparent absence of spurious shiftings justified the proposal to follow up the completion of the Astrographic Chart with the initiation of a photographic "Parallax Durchmusterung."

Observers of double stars are among the most meritorious, and need to be among the most patient and painstaking workers in sidereal astronomy. They are scarcely as numerous as could be wished. Dr. Doberck, distinguished as a computer of stellar orbits, complained in 1882[1590] that data sufficient for the purpose had not been collected for above 30 or 40 binaries out of between five and six hundred certainly or probably within reach. The progress since made is illustrated by Mr. Gore's useful Catalogue of Computed Binaries, including fifty-nine entries, presented to the Royal Irish Academy, June 9, 1890.[1591] Few have done more towards supplying the deficiency of materials than the late Baron Ercole Dembowski of Milan. He devoted the last thirty years of his life, which came to an end January 19, 1881, to the revision of the Dorpat Catalogue, and left behind him a store of micrometrical measures as numerous as they are precise.

Of living observers in this branch, Mr. S. W. Burnham is beyond question the foremost. While pursuing legal avocations at Chicago, he diverted his scanty leisure by exploring the skies with a 6-inch telescope mounted in his back-yard; and had discovered, in May, 1882, one thousand close and mostly very difficult double stars.[1592] Summoned as chief assistant to the new Lick Observatory in 1888, he resumed the work of his predilection with the 36-inch and 12-inch refractors of that establishment. But although devoting most of his attention to much-needed remeasurements of known pairs, he incidentally divided no less than 274 stars, the majority of which lay beyond the resolving power of less keen and effectually aided eyesight. One of his many interesting discoveries was that of a minute companion to α Ursæ Majoris (the first Pointer), which already gives unmistakable signs of orbital movement round the shining orb it is attached to. Another pair, κ Pegasi, detected in 1880, was found in 1892 to have more than completed a circuit in the interim.[1593] Its period of a little over eleven years is the shortest attributable to a *visible* binary system, except that of δ Equulei, provisionally determined by Professor Hussey in 1900 at 5·7 years,[1594] and indicated by spectroscopic evidence to be of uncommon brevity.[1595] Burnham's Catalogue of 1,290 Double Stars, discovered by him from 1871 to 1899,[1596] is a record of unprecedented interest. Nearly all the 690 pairs included in it, 2′ or less than 2′ apart, must be physically connected; and they offer a practically unlimited field for investigation; while the notes, diagrams, and orbits appended profusely to the various entries, are eminently helpful to students and computers. The author is continuing his researches at the Yerkes Observatory, having quitted the Lick establishment in 1892. The first complete enrolment of southern double stars was made by Mr. R. T. A. Innes in 1899.[1597] The couples enumerated, twenty-one per cent. of which are separated by less than one second of arc, are 2,140 in number. They include 305 discovered by himself. Dr. See gathered a rich harvest of nearly 500 new southern pairs with the Lowell 24-inch refractor in 1897.[1598] Professor Hough's discoveries in more northerly zones amount to 623;[1599] Hussey's at Lick to 350; and Aitken's already to over 300.

There is as yet no certainty that the stars of 61 Cygni form a true binary combination. Mr. Burnham, indeed, holds them to be in course of definitive separation; and Professor Hall's observations at Washington, 1879 to 1891, although favouring their physical connection, are far from decisive on the point.[1600] Dr. Wilsing, from certain anomalous displacements of their photographed images, concluded in 1893[1601] the presence of an invisible third member of the system, revolving in a period of twenty-two months; but the effects noticed by him were probably illusory.

Important series of double-star observations were made by Perrotin at Nice in 1883-4;[1602] by Hall, with the 26-inch Washington equatoreal, 1874 to 1891;[1603] by Schiaparelli from 1875 onward; by Glasenapp, O. Stone, Leavenworth, Seabroke, and many besides. Finally, Professor Hussey's revision of the Pulkowa Catalogue[1604] is a work of the *teres atque rotundus* kind, which leaves little or nothing to be desired. The methods employed in double-star determinations remain, at the beginning of the twentieth century, essentially unchanged. The camera has scarcely encroached upon this part of the micrometer's domain.[1605]

A research of striking merit into the origin of binary stars was published in 1892 by Dr. T. J. J. See, in the form of an Inaugural Dissertation for his doctor's degree in the University of Berlin. The main result was to show the powerful effects of tidal friction in prescribing the course of their development from double nebulæ, revolving almost in contact, to double suns, far apart, yet inseparable. The high eccentricities of their eventual orbits were shown to result necessarily from this mode of action, which must operate with enormous strength on closely conjoined, nearly equal masses, such as the rapidly revolving pairs disclosed by the spectroscope. That these are still in an early stage of their life-history is probable in itself, and is re-affirmed by the exceedingly small density indicated for eclipsing stars by the ratio of phase-duration to period.

Stellar photometry, initiated by the elder Herschel, and provided with exact methods by his son at the Cape, by Steinheil and Seidel at Munich, has of late years assumed the importance of a separate department of astronomical research. Two monumental works on the subject, compiled on opposite sides of the Atlantic, were thus appropriately coupled in the bestowal of the Royal Astronomical Society's Gold Medal in 1886. Harvard College Observatory led the way under the able direction of Professor E. C. Pickering. His photometric catalogue of 4,260 stars,[1606] constructed from nearly 95,000 observations of light-intensity during the years 1879-82, constitutes a record of incalculable value for the detection and estimation of stellar variability. It was succeeded in 1885 by Professor Pritchard's "Uranometria Nova Oxoniensis," including photometric determinations of the magnitude of all naked-eye stars, from the pole to ten degrees south of the equator to the number of 2,784. The instrument employed was the "wedge photometer," which measures brightness by resistance to extinction. A wedge of neutral-tint glass, accurately divided to scale, is placed in the path of the stellar rays, when the thickness of it they have power to traverse furnishes a criterion of their intensity. Professor Pickering's "meridian photometer," on the other hand, is based upon Zöllner's principle of equalization effected by a polarising apparatus. After all, however, as Professor Pritchard observed, "the eye is the real photometer," and its judgment can only be valid over a limited range.[1607] Absolute uniformity, then, in estimates made by various means, under varying conditions, and by different observers, is not to be looked for; and it is satisfactory to find substantial agreement attainable and attained. Only in an insignificant fraction of the stars common to the Harvard and Oxford catalogues discordances are found exceeding one-third of a magnitude; a large proportion (71 per cent.) agree within one-fourth, a considerable minority (31 per cent.) within one-tenth of a magnitude.[1608] The Harvard photometry was extended, on the same scale, to the opposite pole in a catalogue of the magnitudes of 7,922 southern stars,[1609] founded on Professor Bailey's observations in Peru, 1889-91. Measurements still more comprehensive were subsequently executed at the primary establishment. With a meridian photometer of augmented power, the surprising number of 473,216 settings were made during the years 1891-98, nearly all by the indefatigable director himself, and they afforded materials for a "Photometric Durchmusterung," published in 1901, including all stars to 7·5 magnitude north of declination -40°.[1610] A photometric zone, 20° wide, has for some time been in course of observation at Potsdam by MM. Müller and Kempf. The instrument employed by them is constructed on the polarising principle as adapted by Zöllner.

Photographic photometry has meanwhile risen to an importance if anything exceeding that of visual photometry. For the usefulness of the great international star-chart now being prepared would be gravely compromised by systematic mistakes regarding the magnitudes of the stars registered upon it. No entirely trustworthy means of determining them have, however, yet been found. There is no certainty as to the relative times of exposure needed to get images of stars representative of successive photometric ranks. All that can be done is to measure the proportionate diameters of such images, and to infer, by the application of a law learned from experience, the varied intensities of light to which they correspond. The law is, indeed, neither simple nor constant. Different investigators have arrived at different formulæ, which, being purely empirical, vary their nature with the conditions of experiment. Probably the best expedient for overcoming the difficulty is that devised by Pickering, of simultaneously photographing a star and its secondary image, reduced in brightness by a known amount.[1611] The results of its use will be exhibited in a catalogue of 40,000 stars to the tenth magnitude, one for each square degree of the heavens. A photographic photometry of all the lucid stars, modelled on the visual photometry of 1884, is promised from the same copious source of novelties. The magnitudes of the stars in the Draper Catalogue were determined, so to speak, spectrographically. The quantity measured in all cases was the intensity of the hydrogen line near G. By the employment of this definite and uniform test, results were obtained, of special value indeed, but in strong disaccord with those given by less exclusive determinations.

Thought, meantime, cannot be held aloof from the great subject upon the future illustration of which so much patient industry is being expended. Nor are partial glimpses denied to us of relations fully discoverable, perhaps, only through centuries of toil. Some important points in cosmical economy have, indeed, become quite clear within the last fifty years, and scarcely any longer admit of a difference of opinion. One of these is that of the true status of nebulæ.

This was virtually settled by Sir J. Herschel's description in 1847 of the structure of the Magellanic clouds; but it was not until Whewell, in 1853, and Herbert Spencer, in 1858, [1612] enforced the conclusions necessarily to be derived therefrom that the conception of the nebulæ as remote galaxies, which Lord Rosse's resolution of many into stellar points had appeared to support, began to withdraw into the region of discarded and half-forgotten speculations. In the Nubeculæ, as Whewell insisted,[1613] "there coexist, in a limited compass and in indiscriminate position, stars, clusters of stars, nebulæ, regular and irregular, and nebulous streaks and patches. These, then, are different kinds of things in themselves, not merely different to us. There are such things as nebulæ side by side with stars and with clusters of stars. Nebulous matter resolvable occurs close to nebulous matter irresolvable."

This argument from coexistence in nearly the same region of space, reiterated and reinforced with others by Mr. Spencer, was urged with his accustomed force and freshness by Mr. Proctor. It is unanswerable. There is no maintaining nebulæ to be simply remote worlds of stars in the face of an agglomeration like the Nubecula Major, containing in its (certainly capacious) bosom *both* stars and nebulæ. Add the facts that a considerable proportion of these perplexing objects are gaseous, and that an intimate relation obviously subsists between the mode of their scattering and the lie of the Milky Way, and it becomes impossible to resist the conclusion that both nebular and stellar systems are parts of a single scheme.[1614]

As to the stars themselves, the presumption of their approximate uniformity in size and brightness has been effectually dissipated. Differences of distance can no longer be invoked to account for dissimilarity in lustre. Minute orbs, altogether invisible without optical aid, are found to be indefinitely nearer to us than such radiant objects as Canopus, Betelgeux, or Rigel. Moreover, intensity of light is perceived to be a very imperfect index to real magnitude. Brilliant suns are swayed from their course by the attractive power of massive yet faintly luminous companions, and suffer eclipse from obscure interpositions. Besides, effective lustre is now known to depend no less upon the qualities of the investing atmosphere than upon the extent and radiative power of the stellar surface. Red stars must be far larger in proportion to the light diffused by them than white or yellow stars.[1615] There can be no doubt that our sun would at least double its brightness were the absorption suffered by its rays to be reduced to the Sirian standard; and, on the other hand, that it would lose half its present efficiency as a light-source if the atmosphere partially veiling its splendours were rendered as dense as that of Aldebaran.

Thus, variety of all kinds is seen to abound in the heavens; and it must be admitted that the consequent insecurity of all hypotheses as to the relative distances of individual stars singularly complicates the question of their allocation in space. Nevertheless, something has been learnt even on that point; and the tendency of modern research is, on the whole, strongly confirmatory of the views expressed by Herschel in 1802. He then no longer regarded the Milky Way as the mere visual effect of an enormously extended stratum of stars, but as an actual aggregation, highly irregular in structure, made up of stellar clouds and groups and nodosities. All the facts since ascertained fit in with this conception, to which Proctor added arguments favouring the view, since adopted by Barnard[1616] and Easton,[1617] that the stars forming the galactic stream are not only situated more closely together, but are also really, as well as apparently, of smaller dimensions than the lucid orbs studding our skies. By the laborious process of isographically charting the whole of Argelander's 324,000 stars, he brought out in 1871[1618] signs of relationship between the distribution of the brighter stars and the complex branchings of the Milky Way, which has been stamped as authentic by Newcomb's recent statistical inquiries.[1619] There is, besides, a marked condensation of stars, especially in the southern hemisphere, towards a great circle inclined some twenty degrees to the galactic plane; and these were supposed by Gould to form with the sun a subordinate cluster, of which the components are seen projected upon the sky as a zone of stellar brilliants.[1620] The zone has, however, galactic rather than solar affinities, and represents, perhaps, not a group, but a stream.

The idea is gaining ground that the Milky Way is designed, in its main outlines, on a spiral pattern, and that its various branches and sections are consequently situated at very different distances from ourselves. Proctor gave a preliminarily interpretation of their complexities on this principle, and Easton of Rotterdam[1621] has renewed the attempt with better success.

A most suggestive delineation of the Milky Way, completed in 1889, after five years of labour, by Dr. Otto Boedicker, Lord Rosse's astronomer at Parsonstown, was published by lithography in 1892. It showed a curiously intricate structure, composed of dimly luminous streams, and shreds, and patches, intermixed with dark gaps and channels. Ramifications from the main trunk ran out towards the Andromeda nebula and the "Bee-hive" cluster in Cancer, involved the Pleiades and Hyades, and, winding round the constellation of Orion, just attained the Sword-handle nebula. The last delicate touches had scarcely been put to the picture, when the laborious eye-and-hand method was, in this quarter, as already in so many others, superseded by a more expeditious process. Professor Barnard took the first photographs ever secured of the true Milky Way, July 28, August 1 and 2, 1889, at the Lick Observatory. Special conditions were required for success; above all, a wide field and a strong light-grasp, both complied with through the use of a 6-inch portrait-lens. Even thus, the sensitive plate needed some hours to pick out the exceedingly faint stars collected in the galactic clouds. These cannot be photographed under the nebulous aspect they wear to the eye; the camera takes note of their real nature, and registers their constituent stars rank by rank. Hence the difficulty of disclosing them. "In the photographs made with the 6-inch portrait-lens," Professor Barnard wrote, "besides myriads of stars, there are shown, for the first time, the vast and wonderful cloud-forms, with all their remarkable structure of lanes, holes, and black gaps, and sprays of stars. They present to us these forms in all their delicacy and beauty, as no eye or telescope can ever hope to see them."[1622] In Plate VI. one of these strange galactic landscapes is reproduced. It occurs in the Bow of Sagittarius, not far from the Trifid nebula, where the aggregations of the Milky Way are more than usually varied and characteristic. One of their distinctive features comes out with particular prominence.

PLATE VI.

Region of the Milky Way in Sagittarius—showing a double black aperture.

Region of the Milky Way in Sagittarius—showing a double black aperture.
Photographed by Professor E. E. Barnard.

It will be noticed that the bright mass near the centre of the plate is tunnelled with dark holes and furrowed by dusky lanes. Such interruptions recur perpetually in the Milky Way. They are exemplified on the largest scale in the great rift dividing it into two branches all the way from Cygnus to Crux; and they are reproduced in miniature in many clusters.

Mr. H. C. Russell, at Sydney in 1890, successfully imitated Professor Barnard's example.[1623] His photographs of the southern Milky Way have many points of interest. They show the great rift, black to the eye, yet densely star-strewn to the perception of the chemical retina; while the "Coal-sack" appears absolutely dark only in its northern portion. His most remarkable discovery, however, was that of the spiral character of the two Nubeculæ. With an effective exposure of four and a half hours, the Greater Cloud came out as "a complex spiral, with two centres"; while the similar conformation of its minor companion developed only after eight hours of persistent actinic action. The revelation is full of significance.

Scarcely less so, although after a different fashion, is the disclosure on plates exposed by Dr. Max Wolf, with a 5-inch lens, in June, 1891, of a vastly extended nebula, bringing some of the leading stars in Cygnus into apparently organic connection with the piles of galactic star-dust likewise involved by it.[1624] Barnard has similarly found great tracts of the Milky Way to be photographically nebulous, and the conclusion seems inevitable that we see in it a prodigious mixed system, resembling that of the Pleiades in point of composition, though differing widely from it in plan of structure. Of corroborative testimony, moreover, is the discovery independently resulting from Gill's and Pickering's photographic reviews, that stars of the first type of spectrum largely prevail in the galactic zone of the heavens.[1625] With approach to that zone, Kapteyn noticed a steady growth of actinic intensity relative to visual brightness in the stars depicted on the Cape Durchmusterung plates.[1626] In other words, stellar light is, in the Milky Way, *bluer* than elsewhere. And the reality of the primitive character hence to be inferred for the entire structure was, in a manner, certified by Mr. McClean's observation that Helium stars—the supposed immediate products of nebulous matter—crowd towards its medial plane.

The first step towards the unravelment of the tangled web of stellar movements was taken when Herschel established the reality, and indicated the direction of the sun's journey. But the gradual shifting backward of the whole of the celestial scenery amid which we advance accounts for only a part of the observed displacements. The stars have motions of their own besides those reflected upon them from ours. All attempts, however, to grasp the general scheme of these motions have hitherto failed. Yet they have not remained wholly fruitless. The community of slow movement in Taurus, upon which Mädler based his famous theory, has proved to be a fact, and one of very extended significance.

In 1870 Mr. Proctor undertook to chart down the directions and proportionate amounts of about 1,600 proper motions, as determined by Messrs. Stone and Main, with the result of bringing to light the remarkable phenomenon termed by him "star-drift."[1627] Quite unmistakably, large groups of stars, otherwise apparently disconnected, were seen to be in progress together, in the same direction and at the same rate, across the sky. An example of this kind of unanimity was alleged by him in the five intermediate stars of the Plough; and that the agreement in thwartwise motion is no casual one is practically demonstrated by the concordant radial velocities determined at Potsdam for four out of the five objects in question. All of these approach the earth at the rate of about eighteen miles a second; and the fifth and faintest, δ Ursæ, though not yet measured, may be held to share their advance. One of them, moreover, ζ Ursæ, alias Mizar, carries with it three other stars—Alcor, the Arab "Rider" of the horse, visible to the naked eye, besides a telescopic and a spectroscopic attendant. So that the group may be regarded as octuple. It is of vast compass. Dr. Höffler assigned to it in 1897[1628]—although on grounds more or less hypothetical—a mean parallax corresponding to a light-journey of 192 years, which would give to the marching squadron a total extent of at least fourteen times the distance from the sun to α Centauri, while implying for its brightest member—ε Ursæ Majoris—the lustre of six hundred suns. The organising principle of this grand scheme must long remain mysterious.

It is no solitary example. Particular association, indeed—as was surmised by Michell far back in the eighteenth century—appears to be the rule rather than an exception in the sidereal system. Stars are bound together by twos, by threes, by dozens, by hundreds. Our own sun is, perhaps, not exempt from this gregarious tendency. Yet the search for its companions has, up to the present, been unavailing. Gould's cluster[1629] seems remote and intangible; Kapteyn's collection of solar stars proved to have been a creation of erroneous data, and was abolished by his unrelenting industry. Rather, we appear to have secured a compartment to ourselves for our long journey through space. A practical certainty has, at any rate, been gained that whatever aggregation holds the sun as a constituent is of a far looser build than the Pleiades or Præsepe. Of all such majestic communities the laws and revolutions remain, as yet, inaccessible to inquiry; centuries may elapse before even a rudimentary acquaintance with them begins to develop; while the economy of the higher order of association, which we must reasonably believe that they unite to compose, will possibly continue to stimulate and baffle human curiosity to the end of time.

FOOTNOTES:

[1369] *Report Brit. Assoc.*, 1868, p. 166. Rutherfurd gave a rudimentary sketch of a classification of the kind in December, 1862, but based on imperfect observation. See *Am. Jour. of Sc.*, vol. xxxv., p. 77.

[1370] *Publicationem*, Potsdam, No. 14, 1884, p. 31.

[1371] Von Konkoly *once* derived from a slow-moving meteor a hydro-carbon spectrum. A. S. Herschel, *Nature*, vol. xxiv., p. 507.

[1372] *Phil. Trans.*, vol. cliv., p. 429.

[1373] *Am. Jour. of Sc.*, vol. xix., p. 467.

[1374] *Photom. Unters.*, p. 243.

[1375] *Spectre Solaire*, p. 38.

[1376] Mr. J. Birmingham, in the Introduction to his Catalogue of Red Stars, adduced sundry instances of colour-change in a direction the opposite to that assumed by Zöllner to be the inevitable result of time. *Trans. R. Irish Acad.*, vol. xxvi., p. 251. A learned discussion by Dr. T. J. J. See, moreover, enforces the belief that Sirius was absolutely *red* eighteen hundred years ago. *Astr. and Astroph.*, vol. xi., p. 269.

[1377] *Phil. Trans.*, vol. clxiv., p. 492.

[1378] *Astr. Nach.*, No. 2,000.

[1379] *Proc. Roy. Soc.*, vols. xvi., p. 31; xvii., p. 48.

[1380] *Annalen der Physik*, Bd. xx., p. 155.

[1381] *Ibid.*, p. 153.

[1382] *Knowledge*, vol. xiv., p. 101.

[1383] *Meteoritic Hypothesis*, p. 380.

[1384] *Phil. Trans.*, vol. cxci. A., p. 128; *Spectra of Southern Stars*, p. 3.

[1385] See the author's *System of the Stars*, p. 84.

[1386] A designation applied by Sir Norman Lockyer to third-type stars.

[1387] See *ante*, p. 198.

[1388] *Bothkamp Beobachtungen*, Heft ii., p. 146.

[1389] *Astr. Nach.*, No. 2,539.

[1390] *Ibid.*, No. 2,548; *Observatory*, vol. vi., p. 332.

[1391] *Month. Not.*, vol. xlvii., p. 92.

[1392] *Publ. Astr. Pac. Soc.*, vol. i., p. 80; *Observatory*, vol. xiii., p. 46.

[1393] *Lockyer, Proc. Roy. Soc.*, vol. lvii., p. 173.

[1394] *Astr. Nach.*, No. 3,129.

[1395] *Month. Not.*, vol. lix., p. 505.

[1396] *Astr. Nach.*, No. 2,581.

[1397] *Ibid.*, Nos. 2,651-2.

[1398] *Ibid.*, No. 3,051; *Astr. and Astrophysics*, vol. xi., p. 25; Bélopolsky, *Astr. Nach.*, No. 3,129.

[1399] *Comptes Rendus*, t. lxv., p. 292.

[1400] *Copernicus*, vol. iii., p. 207.

[1401] *System of the Stars*, p. 70; *Harvard Annals*, vol. xxviii., pt. ii., p. 243 (Miss Cannon).

[1402] *Potsdam Publ.*, No. 14, p. 17.

[1403] *Proc. Roy. Soc.*, vol. xlix., p. 33.

[1404] Miss A. J. Cannon, *Harvard Annals*, vol. xxviii., pt. ii., p. 141.

[1405] *Astr. and Astroph.*, vol. xiii., p. 448.

[1406] *Potsdam Publ.*, No. 2.

[1407] The results of Von Konkoly's extension of Vogel's work to 15° of south declination were published in *O Gyalla Beobachtungen*, Bd. viii., Th. ii., 1887.

[1408] *Astroph. Jour.*, vols. viii., p. 237; ix., p. 271.

[1409] *Ibid.*, vol. ix., p. 119.

[1410] *Phil. Trans.*, vol. cliv., p. 413. Some preliminary results were embodied in a "note" communicated to the Royal Society, February 19, 1863 (*Proc. Roy. Soc.*, vol. xii., p. 444).

[1411] *Bothkamp Beob.*, Heft i., p. 25.

[1412] *Astroph. Jour.*, vol. vi., p. 423.

[1413] *Phil. Trans.*, vol. cliv., p. 429, *note*.

[1414] *Month. Not.*, vol. xxiii., p. 180.

[1415] *Proc. Roy. Soc.*, vol. xxv., p. 446.

[1416] *Phil. Trans.*, vol. clxxi., p. 669; *Atlas of Stellar Spectra*, p. 22.

[1417] *Astr. Nach.*, No. 2,301; *Monatsb.*, Berlin, 1879, p. 119; 1880, p. 192.

[1418] *Jour. de Physique*, t. v., p. 98.

[1419] *System of the Stars*, p. 39.

[1420] See *ante*, p. 198.

[1421] *Proc. Roy. Soc.*, vol. xlviii., p. 314.

[1422] *Harvard Circulars*, Nos. 12, 18; *Astroph. Jour.*, vol. v., p. 92.

[1423] *Astroph. Jour.*, vol. vi., p. 233.

[1424] McClean, *Phil. Trans.*, vol. cxci. A., p. 129.

[1425] *Proc. Roy. Soc.*, vol. lxii., p. 417.

[1426] *Ibid.*, April 27, 1899; *Astroph. Jour.*, vol. x., p. 272.

[1427] *Astr. Nach.*, No. 3,565.

[1428] *Ibid.*, No. 3,583.

[1429] Lunt, *Astroph. Jour.*, vol. xi., p. 262; *Proc. Roy. Soc.*, vol. lxvi., p. 44; Lockyer, *ibid.*, November 23, 1899; *Nature*, vol. lxi., p. 263.

[1430] *Die Spectralanalyse*, p. 314.

[1431] *Henry Draper Memorial, First Ann. Report*, 1887.

[1432] *Mem. Amer. Acad.*, vol. xi., p. 215.

[1433] *Harvard Annals*, vol. xxvii.

[1434] *Harvard Annals*, vol. xxviii., parts i. and ii.

[1435] See *ante*, p. 201.

[1436] *Phil. Trans.*, vol. clviii., p. 529.

[1437] Schellen, *Die Spectralanalyse*, Bd. ii., p. 326 (ed. 1883).

[1438] *Proc. Roy. Soc.*, vol. xx., p. 386.

[1439] *System of the Stars*, p. 199.

[1440] Pickering, *Am. Jour. of Sc.*, vol. xxxix., p. 46; Vogel, *Astr. Nach.* No. 3,017.

[1441] *Sitzungsberichte*, Berlin, May 2, 1901; *Astroph. Jour.*, vol. xiii., p. 324.

[1442] The “relative orbit” of a double star is that described by one round the other as a fixed point. Micrometrical measures are always thus executed. But in reality both stars move in opposite directions, and at rates inversely as their masses round their common centre of gravity.

[1443] Vogel, *Astr. Nach.*, Nos. 3,017, 3,039.

[1444] Huggins, *Pres. Address*, 1891; Cornu, *Sur la Méthode Doppler-Fizeau* p. D. 38.

[1445] *Sitzungsb.*, Berlin, 1890, p. 401; *Astr. Nach.*, No. 2,995.

[1446] *Ibid.*

[1447] *Astroph. Jour.*, vol. v., p. 1; Newall, *Month. Not.*, vol. lvii., p. 575.

[1448] *Bull. de l’Acad. de St. Pétersb.*, tt. vi., viii.

[1449] *Astroph. Jour.*, vol. x., p. 177; *Month. Not.*, vol. lx., p. 418; Vogel, *Sitzungsb.*, Berlin, April 19, 1900.

[1450] *Month. Not.*, vol. lx., p. 595.

[1451] Hussey, *Astr. Jour.*, No. 484.

[1452] *Astroph. Jour.*, vols. x, p. 180; xiv., p. 140; *Lick Bulletin*, No. 4; Bélopolsky, *Astr. Nach.*, No. 3,637.

[1453] The significance of the name “El Ghoul” leaves little doubt that the Arab astronomers took note of this star’s variability. E. M. Clerke, *Observatory*, vol. xv., p. 271.

[1454] *Phil. Trans.*, vol. lxxiii., p. 484.

[1455] *Proc. Amer. Acad.*, vol. xvi., p. 17; *Observatory*, vol. iv., p. 116. For a preliminary essay by T. S. Aldis, see *Phil. Mag.*, vol. xxxix., p. 363, 1870.

[1456] *Astr. Nach.*, No. 2,947.

[1457] *Astr. Jour.*, Nos. 165-6, 255-6, 509. See also *Knowledge*, vol. xv., p. 186.

[1458] Bauschinger, *V. J. S. Astr. Ges.*, Jahrg. xxix.; but *cf.* Searle, *Harvard Annals*, vol. xxix., p. 223; Boss, *Astr. Jour.*, No. 343.

[1459] *Comptes Rendus*, t. cxx., p. 125.

[1460] Myers, *Astroph. Jour.*, vol. vii., p. 1; A. W. Roberts, *Ibid.*, vol. xiii., p. 181.

[1461] *Proc. R. Irish Ac.*, July, 1884.

[1462] *Ibid.*, vol. i., p. 97.

[1463] *Astr. Jour.*, Nos. 179, 180.

[1464] *Ibid.*, Nos. 300, 379.

[1465] *Astr. Jour.*, Nos. 491-2.

[1466] *System of the Stars*, p. 125.

[1467] *Proc. Roy. Soc.*, vol. xv., p. 146.

[1468] Weiss, *Astr. Nach.*, No. 1,590; Espin, *Ibid.*, No. 3,200.

[1469] *Comptes Rendus*, t. lxxxiii., p. 1172.

[1470] *Monatsb.*, Berlin, 1877, pp. 241, 826.

[1471] *Copernicus*, vol. ii., p. 101.

[1472] Burnham, *Month. Not.*, vol. lii., p. 457.

[1473] *Astr. Nach.*, No. 2,682.

[1474] A. Hall, *Am. Jour. of Sc.*, vol. xxxi., p. 301.

[1475] Young, *Sid. Messenger*, vol. iv., p. 282; Hasselberg, *Astr. Nach.*, No. 2,690.

[1476] *Report Brit. Assoc.*, 1885, p. 935.

[1477] *Month. Not.*, vol. xlvii., p. 54.

[1478] *Nature*, vol. xxxii., p. 522.

[1479] *Astr. Nach.*, Nos. 1,267, 2,715.

[1480] *Month. Not.*, vol. xxi., p. 32.

[1481] *Observatory*, vol. viii., p. 335.

[1482] *Astr. Nach.*, No. 3,118; *Astr. and Astroph.*, vol. xi., p. 907.

[1483] *Cape Results*, p. 137.

[1484] *Trans. R. Soc. of Edinburgh*, vol. xxvii., p. 51; *Astr. and Astroph.*, August, 1892, p. 593.

[1485] Vogel, *Astr. Nach.*, No. 3,079.

[1486] *Observatory*, vol. xv., p. 287; Seeliger, *Astr. Nach.*, No. 3,118; *Astr. and Astroph.*, vol. xi., p. 906.

[1487] Ranyard, *Knowledge*, vol. xv., p. 110.

[1488] *Proc. Roy. Soc.*, vol. li., p. 492.

[1489] Burnham, *Month. Not.*, vol. liii., p. 58.

[1490] *Astr. Nach.*, Nos. 3,118, 3,143.

[1491] Renz, *Ibid.*, Nos. 3,119, 3,238; Huggins, *Astr. and Astroph.*, vol. xiii., p. 314.

[1492] *Astr. Nach.*, No. 3,111.

[1493] Bélopolsky, *Astr. Nach.*, No. 3,120.

[1494] *Nature*, September 15, 1892.

[1495] *Astr. Nach.*, Nos. 3,122, 3,129.

[1496] *Ibid.*, No. 3,133; *Astr. and Astroph.*, vol. xi., p. 715.

[1497] *Publ. Astr. Pac. Soc.*, vol. iv., p. 244.

[1498] Barnard, *Astroph. Jour.*, vol. xiv., p. 152; Campbell, *Observatory*, vol. xxiv., p. 360.

[1499] *Pop. Astr.*, March, 1895, p. 307.

[1500] *Harvard Circular*, No. 4, December 20, 1895. The first Nova Persei was spectrographically recorded in 1887.

[1501] Vogel, *Sitzungsb.*, Berlin, April 19, 1900, p. 389.

[1502] Sidgreaves, *Observatory*, vol. xxiv., p. 191.

[1503] *Ibid.*, *Knowledge*, vol. xxv., p. 10.

[1504] *Lick Bulletin*, No. 8.

[1505] *Astr. Nach.*, No. 3,736.

[1506] *Astroph. Jour.*, vol. xiv., p. 167.

[1507] *Lick Bulletin*, No. 10.

[1508] *Astroph. Jour.*, vols. xiv., p. 293; xv., p. 129.

[1509] *Cf.* the theories on the subject of M. Wolf, *Astr. Nach.*, Nos. 3,752, 3,753; Kapteyn, *Ibid.*, No. 3,756; F. W. Very, *Ibid.*, No. 3,771; and W. E. Wilson, *Proc. Roy. Dublin Soc.*, No. 45, p. 556.

[1510] *Phil. Trans.*, vol. cliv., p. 437.

[1511] *Phil. Trans.*, vol. clviii., p. 540. The true proportion seems to be about one-tenth (*Harvard Annals*, vol. xxvi., pt. ii., p. 205), the Tulse Hill working-list having been formed of specially selected objects.

[1512] Scheiner, *Astr. Nach.*, No. 3,476; *Astroph. Jour.*, vol. vii., p. 231; Campbell, *Ibid.*, vols. ix., p. 312; x., p. 22.

[1513] *Proc. Roy. Soc.*, vols. xlvi., p. 40; xlviii., p. 202.

[1514] *Publ. Astr. Pac. Soc.*, vol. ii., p. 265; *Proc. Roy. Soc.*, vol. xlix., p. 399.

[1515] *Astr. Nach.*, No 3,549.

[1516] *Atlas of Stellar Spectra*, p. 125.

[1517] *Knowledge*, vol. xix., p. 39.

[1518] *Astr. Nach.*, Nos. 1,366, 1,391, 1,689; Chambers, *Descriptive Astr.* (3rd ed.), p. 543; Flammarion, *L'Univers Sidéral*, p. 818.

[1519] *Month. Not.*, vol. li., p. 94.

[1520] *Ibid.*, vol. lix., p. 372.

[1521] *Ibid.*, vol. lx., p. 424.

[1522] Dreyer, *Ibid.*, vol. lii., p. 100.

[1523] *Wash. Obs.*, vol. xxv., App. 1.

[1524] *Am. Jour. of Sc.*, vol. xiv., p. 433; C. Dreyer, *Month. Not.*, vol. xlvii., p. 419.

[1525] *Ibid.*, vol. li., p. 496.

[1526] Reproduced in *Knowledge*, April, 1893.

[1527] Unless an exception be found in the Pleiades nebulæ, which may be assumed to share the small apparent movement of the stars they adhere to.

[1528] *Abhandl. Akad. der Wiss.*, Leipzig, 1857, Bd. iii., p. 295.

[1529] *Month. Not.*, vol. lii., p. 31.

[1530] *Proc. Roy. Soc.*, 1874, p. 251.

[1531] *Publ. Astr. Pac. Soc.*, vol. ii., p. 278.

[1532] *System of the Stars*, p. 257.

[1533] *Proc. Roy. Soc.*, vol. xlix., p. 399.

[1534] *Potsdam Publ.*, Bd. vii., Th. i.

[1535] *Astr. Nach.*, No. 2,714; Schönfeld, *V. J. S. Astr. Ges.*, Jahrg. xxi., p. 58.

[1536] *Astroph. Journ.*, vol. xiii., p. 80.

[1537] *Proc. Roy. Soc.*, vol. xxxiii., p. 425; *Report Brit. Assoc.*, 1882, p. 444. An impression of the four lower lines in the same spectrum was almost simultaneously obtained by Dr. Draper. *Comptes Rendus*, t. xciv., p. 1243.

[1538] *Proc. Roy. Soc.*, vol. xlviii., p. 213.

[1539] *Month. Not.*, vol. xlviii., p. 360.

[1540] *Proc. Roy. Soc.*, vol. xlvi., p. 40; *System of the Stars*, p. 79.

[1541] *Sitzungsb.*, Berlin, February 13, 1890.

[1542] *Wash. Obs.*, vol. xxv., App. i., p. 226.

[1543] *Comptes Rendus*, t. xcii., p. 261.

[1544] *Month. Not.*, vol. xliii., p. 255.

[1545] *Harvard Annals*, vol. xviii., p. 116.

[1546] *Sid. Mess.*, vol. ix., p. 1.

[1547] *Knowledge*, vol. xv., p. 191.

[1548] *Month. Not.*, vol. xlix., p. 65.

[1549] *System of the Stars*, p. 269.

[1550] *Astr. Nach.*, Nos. 2,749, 2,754.

[1551] Vogel, *Astr. Nach.*, 2,854.

[1552] *Nature*, vol. xliii., p. 419.

[1553] *L'Astronomie*, t. xl., p. 171.

[1554] *Astr. Nach.*, Bände xlvii., p. 1; xlviii., p. 1; xlix., p. 81. Pickering, *Mem. Am. Ac.*, vol. xi., p. 180.

[1555] Gould on Celestial Photography, *Observatory*, vol. ii., p. 16.

[1556] *Annals N. Y. Acad. of Sciences*, vol. vi., p. 239, 1892; Elkin, *Publ. Astr. Pac. Soc.*, vol. iv., p. 134.

[1557] *Trans. Yale Observatory*, vol. i., pt. i.

[1558] *Astroph. Jour.*, vol. xiii., p. 56.

[1559] *Astr. Nach.*, No. 2,719.

[1560] *Ibid.*, No. 2,726.

[1561] *Ibid.*, No. 2,730.

[1562] *Month. Not.*, vol. xlvii., p. 24.

[1563] *Les Mondes*, t. iii., p. 529.

[1564] Mouchez, *Comptes Rendus*, t. cvi., p. 912.

[1565] *Astr. Nach.*, No. 3,422.

[1566] *Ibid.*, No. 3,441.

[1567] *Ibid.*, Nos. 3,018, 3,032.

[1568] *Journ. Brit. Astr. Assoc.*, vol. ix., p. 133.

[1569] *Astr. Nach.*, No. 3,253.

[1570] *Observatory*, vol. xxi., pp. 351, 386.

[1571] Reproduced in *Astroph. Journ.*, vol. xi., p. 324.

[1572] *Ibid.*, p. 347.

[1573] *Astr. Nach.*, No. 3,704.

[1574] *Sitzungsb. Bayer. Akad.*, March 23, 1901.

[1575] *Annals of the Cape Observatory*, vols. iii., iv., v.

[1576] *Month. Not.*, vol. lx., p. 381.

[1577] D. Klumpke, *Observatory*, vol. xv., p. 305.

[1578] Gilbert, *Sid. Mess.*, vol. i., p. 288.

[1579] *Astr. Papers for the Amer. Ephemeris*, vol. viii., pt. ii.

[1580] *Nature*, vol. xxiv., p. 91; *Dunsink Observations*, pt. v., 1884.

[1581] Elkin, *Report for 1891-92*, p. 25; Newcomb, *The Stars*, p. 151.

[1582] *Annals of the Cape Observatory*, vol. viii., pt. ii. Some of the measures were made by Messrs. Finlay and de Sitter.

[1583] *Astr. Nach.*, No. 3,483; *Observatory*, vol. xxi., p. 180.

[1584] *Annalen der Sternwarte in Leiden*, Bd. vii.

[1585] *Report of Harvard Conference in 1898* (Snyder).

[1586] *Researches in Stellar Parallax*, pt. ii., 1892.

[1587] *V. J. S. Astr. Ges.*, Jahrg., xxviii., p. 117.

[1588] *Bulletin de la Carte du Ciel*, No. 1, p. 262.

[1589] *Publ. of the Astr. Laboratory at Groningen*, No. 1.

[1590] *Nature*, vol. xxvi., p. 177.

[1591] *Proc. R. Irish Acad.*, vol. i., p. 571, ser. iii.

[1592] *Mem. R. A. S.*, vol. xlvii., p. 178.

[1593] *Astr. Nach.*, No. 3,142.

[1594] *Publ. Astr. Pac. Soc.*, No. 76.

[1595] Campbell, *Lick Bulletin*, No. 4.

[1596] *Publ. Yerkes Observatory*, vol. i., 1900.

[1597] *Annals Cape Observatory*, vol. ii., pt. ii.

[1598] *Astr. Jour.*, Nos. 431-2.

[1599] W. J. Hussey, *Publ. Astr. Pac. Soc.*, No. 74.

[1600] *Astr. Jour.*, No. 258.

[1601] *Sitzungsberichte*, Berlin, October 26, 1893.

[1602] *Annales de l'Obs. de Nice*, t. ii.

[1603] *Washington Observations*, 1888, App. i.

[1604] *Publ. Lick Observatory*, vol. v., 1901.

[1605] T. Lewis, *Observatory*, vol. xvi., p. 312.

[1606] *Harvard Annals*, vol. xiv., pt. i., 1884.

[1607] *Observatory*, vol. viii., p. 309.

[1608] *Month. Not.*, vol. xlvi., p. 277.

[1609] *Harvard Annals*, vol. xxxiv.

[1610] *Ibid.*, vol. xlv.

[1611] *Carte Phot. du Ciel. Réunion du Comité Permanent*, Paris, 1891, p. 100.

[1612] *Essays* (2nd ser.), *The Nebular Hypothesis*.

[1613] *On the Plurality of Worlds*, p. 214 (2nd ed.).

[1614] Proctor, *Month. Not.*, vol. xxix., p. 342.

[1615] This remark was first made by J. Michell, *Phil. Trans.*, vol. lvii., p. 25 (1767).

[1616] *Pop. Astr.*, No. 45.

[1617] *Astroph. Jour.*, vol. i., p. 220.

[1618] *Month. Not.*, vols. xxxi., p. 175; xxxii., p. 1.

[1619] *The Stars*, p. 273.

[1620] *System of the Stars*, p. 384; *Old and New Astronomy*, p. 749 (Ranyard).

[1621] *Astroph. Jour.*, vol. xii., p. 156.

[1622] *Publ. Astr. Pac. Soc.*, vol. ii., p. 242.

[1623] *Month. Not.*, vol. li., pp. 40, 97. For reproductions of some of the photographs in question, see *Knowledge*, vol. xiv., p. 50.

[1624] *Astr. Nach.*, No. 3,048; *Observatory*, vol. xiv., p. 301.

[1625] *Proc. Roy. Inst.*, May 29, 1891 (Gill).

[1626] *Annals Cape Obs.*, iii., Introduction, p. 22.

[1627] *Proc. Roy. Soc.*, vol. xviii., p. 169.

[1628] *Astr. Nach.*, No. 3,456; *Observatory*, vol. xxi., p. 65; Newcomb, *The Stars*, p. 80.

[1629] *Month. Not.*, vol. xl., p. 249.

CHAPTER XIII

METHODS OF RESEARCH

Comparing the methods now available for astronomical inquiries with those in use forty years ago, we are at once struck with the fact that they have multiplied. The telescope has been supplemented by the spectroscope and the photographic camera. Now, this really involves a whole world of change. It means that astronomy has left the place where she dwelt apart in rapt union with mathematics, indifferent to all things on earth save only to those mechanical improvements which should aid her to penetrate further into the heavens, and has descended into the forum of human knowledge, at once a suppliant and a patron, alternately invoking help from and promising it to each of the sciences, and patiently waiting upon the advances of all. The science of the heavenly bodies has, in a word, become a branch of terrestrial physics, or rather a higher kind of integration of all their results. It has, however, this leading peculiarity, that the materials for the whole of its inquiries are telescopically furnished. They are such as come very imperfectly, or not at all, within the cognisance of the unarmed eye.

Spectroscopic and photographic apparatus are simply additions to the telescope. They do not supersede or render it of less importance. On the contrary, the efficacy of their action depends primarily upon the optical qualities of the instruments they are attached to. Hence the development, to their fullest extent, of the powers of the telescope is of vital moment to the progress of modern physical astronomy, while the older mathematical astronomy could afford to remain comparatively indifferent to it.

The colossal Rosse reflector still marks, as to size, the *ne plus ultra* of performance in that line. A mirror four feet in diameter was, however, sent out to Melbourne by the late Thomas Grubb of Dublin in 1870. This is mounted in the Cassegrainian manner, so that the observer looks straight through it towards the object viewed, of which he really sees a twice-reflected image. The dust-laden atmosphere of Melbourne is said to impede very seriously the usefulness of this originally fine instrument.

It may be doubted whether so large a spectrum will ever again be constructed. A new material for the mirrors of reflecting telescopes, proposed by Steinheil in 1856, and independently by Foucault in 1857,[1630] has in a great measure superseded the use of a metallic alloy. This is glass upon which a thin film of silver has been deposited by a chemical process originally invented by Liebig. It gives a peculiarly brilliant reflective surface, throwing back more light than a metallic mirror of the same area, in the proportion of about sixteen to nine. Resilvering, too, involves much less risk and trouble than repolishing a speculum. The first use of this plan on a large scale was in an instrument of thirty-six inches aperture, finished by Calver for Dr. Common in 1879. To its excellent qualities turned to account with rare skill, his triumphs in celestial photography are mainly due. A more daring experiment was the construction and mounting, by Dr. Common himself, of a 5-foot reflector. But the first glass disc ordered from France for the purpose proved radically defective. When figured, polished, and silvered, towards the close of 1888, it gave elliptical instead of circular star-images.[1631] A new one had to be procured, and was ready for astronomical use in 1891. The satisfactory nature of its performance is vouched for by the observations made with it upon Jupiter's new satellite in December, 1892. This instrument, to which a Newtonian form has been given, had no rival in respect of light-concentration at the time when it was built. It has now two—the Paris 50-inch refractor and the Yerkes 5-foot reflector.

It is, however, in the construction of refracting telescopes that the most conspicuous advances have recently been made. The Harvard College 15-inch achromatic was mounted and ready for work in June, 1847. A similar instrument had already for some years been in its place at Pulkowa. It was long before the possibility of surpassing these masterpieces of German skill presented itself to any optician. For fifteen years it seemed as if a line had been drawn just there. It was first transgressed in America. A portrait-painter of Cambridgeport, Massachusetts, named Alvan Clark, had for some time amused his leisure with grinding lenses, the singular excellence of which was discovered in England by Mr. Dawes in 1853.[1632] Seven years passed, and then an order came from the University of Mississippi for an object-glass of the unexampled size of eighteen inches. An experimental glance through it to test its definition resulted, as we have seen, in the detection of the companion of Sirius, January 31, 1862. It never reached its destination in the South. War troubles supervened, and it was eventually sent to Chicago, where it served Professor Hough in his investigations of Jupiter, and Mr. Burnham in his scrutiny of double stars.

The next step was an even longer one, and it was again taken by a self-taught optician, Thomas Cooke, the son of a shoemaker at Allerthorpe, in the East Riding of Yorkshire. Mr. Newall of Gateshead ordered from him in 1863 a 25-inch object-glass. It was finished early in 1868, but at the cost of shortening the life of its maker, who died October 19, 1868, before the giant refractor he had toiled at for five years was completely mounted. This instrument, the fine qualities of which had long been neutralized by an unfavourable situation, was presented by Mr. Newall to the University of Cambridge, a few weeks before his death, April 21, 1889. Under the care of his son, Mr. Frank Newall, it has proved highly efficient in the delicate work of measuring stellar radial motions.

Close upon its construction followed that of the Washington 26-inch, for which twenty thousand dollars were paid to Alvan Clark. The most illustrious point in its career, entered upon in 1873, has been the discovery of the satellites of Mars. Once known to be there, these were, indeed, found to be perceptible with very moderate optical means (Mr. Wentworth Erck saw Deimos with a 7-inch Clark); but the first detection of such minute objects is a feat of a very different order from their subsequent observation. Dr. See's perception with this instrument, in 1899, of Neptune's cloud-belts, and his refined series of micrometrical measures of the various planets, attest the unimpaired excellence of its optical qualities.

It held the primacy for more than eight years. Then, in December, 1880, the place of honour had to be yielded to a 27-inch achromatic, built by Howard Grubb (son and successor of Thomas Grubb) for the Vienna Observatory. This, in its turn, was surpassed by two of respectively 29-1/2 and 30 inches, sent by Gautier of Paris to Nice, and by Alvan Clark to Pulkowa; and an object-glass, three feet in diameter, was in 1886 successfully turned out by the latter firm for the Lick Observatory in California. The difficulties, however, encountered in procuring discs of glass of the size and purity required for this last venture seemed to indicate that a term to progress in this direction was not far off. The flint was, indeed, cast with comparative ease in the workshops of M. Feil at Paris. The flawless mass weighed 170 kilogrammes, was over 38 inches across, and cost 10,000 dollars. But with the crown part of the designed achromatic combination things went less smoothly. The production of a perfect disc was only achieved after *nineteen* failures, involving a delay of more than two years; and the glass for a third lens, designed to render the telescope available at pleasure for photographic purposes, proved to be strained, and consequently went to pieces in the process of grinding. It has been replaced by one of 33 inches, with which a series of admirable lunar and other photographs have been taken.

Nor is the difficulty in obtaining suitable material the only obstacle to increasing the size of refractors. The "secondary spectrum," as it is called, also interposes a barrier troublesome to surmount. True achromatism cannot be obtained with ordinary flint and crown-glass; and although in lenses of "Jena glass," outstanding colour is reduced to about one-sixth its usual amount, their term of service is fatally abridged by rapid deterioration. Nevertheless, a 13-inch objective of the new variety was mounted at Königsberg in 1898; and discs of Jena crown and flint, 23 inches across, were purchased by Brashear at the Chicago Exhibition of 1893. An achromatic combination of three kinds of glass, devised by Mr. A. Taylor[1633] for Messrs. Cooke of York, has less serious drawbacks, but has not yet come into extensive use. Meanwhile, in giant telescopes affected to the full extent by chromatic aberration, such as the Lick and Yerkes refractors, the differences of focal length for the various colours are counted by inches,[1634] and this not through any lack of skill in the makers, but by the necessity of the case. Embarrassing consequences follow. Only a small part of the spectrum of a heavenly body, for instance, can be distinctly seen at one time; and a focal adjustment of half an inch is required in passing from the observation of a planetary nebula to that of its stellar nucleus. A refracting telescope loses, besides, one of its chief advantages over a reflector when its size is increased beyond a certain limit. That advantage is the greater luminosity of the images given by it. Considerably more light is transmitted through a glass lens than is reflected from an equal metallic surface. But only so long as both are of moderate dimensions. For the glass necessarily grows in thickness as its area augments, and consequently stops a larger percentage of the rays it refracts. So that a point at length arrives—fixed by the late Dr. Robinson at a diameter a little short of 3 feet[1635]—where the glass and the metal are, in this respect, on an equality; while above it the metal has the advantage. And since silvered glass gives back considerably more light than speculum metal, the stage of equalisation with lenses is reached proportionately sooner where this material is employed.[1636]

The most distinctive faculty of reflectors, however, is that of bringing rays of all refrangibilities to a focus together. They are naturally achromatic. None of the beams they collect are thrown away in colour-fringes, obnoxious both in themselves and as a waste of the chief object of astrophysicists' greed—light. Reflectors, then, are in this respect specially adapted to photographic and spectrographic use. But they have a countervailing drawback. The penalties imposed by bigness are for them peculiarly heavy. Perfect definition becomes with increasing size, more and more difficult to attain; once attained, it becomes more and more difficult to keep. For the huge masses of material employed to form great object-glasses or mirrors tend with every movement to become deformed by their own weight. Now, the slightest bending of a mirror is fatal to its performance, the effect being doubled by reflection; while in a lens alteration of figure is compensated by the equal and contrary flexures of the opposing surfaces, so that the emergent beams pursue much the same paths as if the curves of the refracting medium had remained theoretically perfect. For this reason work of precision must remain the province of refracting telescopes, although great reflectors retain the primacy in the portraiture of the heavenly bodies, as well as in certain branches of spectroscopy. Professor Hale, accordingly, summarised a valuable discussion on the subject by asserting[1637] "that the astrophysicist may properly consider the reflector to be an even more important part of his instrumental equipment than the refractor." A new era in its employment west of the Atlantic opened with the transfer from Halifax to Mount Hamilton of the Crossley reflector. Its prerogatives in nebular photography were splendidly indicated in 1899 by Professor Keeler's exquisite and searching portrayals of the cloud-worlds of space, and those obtained two years later, with a similar, though smaller, instrument, by Professor Ritchey of the Yerkes Observatory, were fully comparable with them. The performances of the Yerkes 5-foot reflector still belong to the future.

Ambition as regards telescopic power is by no means yet satisfied. Nor ought it to be. The advance of astrophysical researches of all kinds depends largely upon light-grasp. For the spectroscopic examination of stars, for the measurement of their motions in the line of sight, for the discovery and study of nebulæ, for stellar and nebular photography, the cry continually is "more light." There is no enterprising head of an observatory but must feel cramped in his designs if he can command no more than 14 or 15 inches of aperture, and he aspires to greater instrumental capacity, not merely with a view to the chances of discovery, but for the steady prosecution of some legitimate line of inquiry. Thus projects of telescope-building on a large scale are rife, and some obtain realisation year by year. Sir

Howard Grubb finished in 1893 a 28-inch achromatic for the Royal Observatory, Greenwich; the Thompson equatoreal, mounted at the same establishment in 1897, carries on a single axis a 26-inch photographic refractor and a 30-inch silvered-glass reflector; the Victoria telescope, inaugurated at the Cape in 1901, comprises a powerful spectrographic apparatus, together with a chemically corrected 24-inch refractor, the whole being the munificent gift of Mr. Frank McClean; at Potsdam, at Meudon, at Paris, at Alleghany, engines for light-concentration have been, or shortly will be, erected of dimensions which, two generations back, would have seemed extravagant and impossible.

Perhaps the finest, though not absolutely the greatest, among them, marked the summit and end of the performances of Alvan G. Clark, the last survivor of the Cambridgeport firm.

In October, 1892, Mr. Yerkes of Chicago offered an unlimited sum for the provision of the University of that city with a “superlative” telescope. And it happened, fortunately, that a pair of glass discs, nearly 42 inches in diameter, and of perfect quality, were ready at hand. They had been cast by Mantois for the University of Southern California, when the erection of a great observatory on Wilson’s Peak was under consideration. In the Clark workshop they were combined into a superb objective, brought to perfection by trials and delicate touches extending over nearly five years. Then the maker accompanied it to its destination, by the shore of a far Western Lake Geneva, and died immediately after his return, June 9, 1897. Nor has the implement of celestial research he just lived to complete been allowed to “rust unburnished.” Manipulated by Hale, Burnham, and Barnard, it has done work that would have been impracticable with less efficient optical aid. Its construction thus marks a noticeable enlargement of astronomical possibilities, exemplified—to cite one among many performances—by Barnard’s success in keeping track of cluster-variables when below the common limit of visual perception.

With the Lick telescope results have also been achieved testifying to its unsurpassed excellence. Holden’s and Schaeberle’s views of planetary nebulæ, Burnham’s and Hussey’s hair’s-breadth star-splitting operations, Keeler’s measurements of nebular radial motion, Barnard’s detections and prolonged pursuit of faint comets, his discovery of Jupiter’s tiny moon, Campbell’s spectroscopic determinations—all this could only have been accomplished, even by an exceptionally able and energetic staff, with the aid of an instrument of high power and quality. But there was another condition which should not be overlooked.

The best telescope may be crippled by a bad situation. The larger it is, indeed, the more helpless is it to cope with atmospheric troubles. These are the worst plagues of all those that afflict the astronomer. No mechanical skill avails to neutralise or alleviate them. They augment with each increase of aperture; they grow with the magnifying powers applied. The rays from the heavenly bodies, when they can penetrate the cloud-veils that too often bar their path, reach us in an enfeebled, scattered, and disturbed condition. Hence the twinkling of stars, the "boiling" effects at the edges of sun, moon, and planets; hence distortions of bright, effacements of feeble telescopic images; hence, too, the paucity of the results obtained with many powerful light-gathering machines.

No sooner had the Parsonstown telescope been built than it became obvious that the limit of profitable augmentation of size had, under climatic conditions at all nearly resembling those prevailing there, been reached, if not overpassed; and Lord Rosse himself was foremost to discern the need of pausing to look round the world for a clearer and stiller air than was to be found within the bounds of the United Kingdom. With this express object Mr. Lassell transported his 2-foot Newtonian to Malta in 1852, and mounted there, in 1860, a similar instrument of fourfold capacity, with which, in the course of about two years, 600 new nebulæ were discovered. Professor Piazzi Smyth's experiences during a trip to the Peak of Teneriffe in 1856 in search of astronomical opportunities[1638] gave countenance to the most sanguine hopes of deliverance, at suitable elevated stations, from some of the oppressive conditions of low-level star-gazing; yet for a number of years nothing effectual was done for their realisation. Now, at last, however, mountain observatories are not only an admitted necessity but an accomplished fact; and Newton's long forecast of a time when astronomers would be compelled, by the developed powers of their telescopes, to mount high above the "grosser clouds" in order to use them,[1639] had been justified by the event.

James Lick, the millionaire of San Francisco, had already chosen, when he died, October 1, 1876, a site for the new observatory, to the building and endowment of which he had devoted a part of his large fortune. The situation of the establishment is exceptional and splendid. Planted on one of the three peaks of Mount Hamilton, a crowning summit of the Californian Coast Range, at an elevation of 4,200 feet above the sea, in a climate scarce rivalled throughout the world, it commands views both celestial and terrestrial which the lover of nature and astronomy may alike rejoice in. Impediments to observation are there found to be most materially reduced. Professor Holden, who was appointed, in 1885, president of the University of California and director of the new observatory affiliated to it, stated that during six or seven months of the year an unbroken serenity prevails, and that half the remaining nights are clear.[1640] The power of continuous work thus afforded is of itself an inestimable advantage; and the high visual excellences testified to by Mr. Burnham's discovery, during a two months' trip to Mount Hamilton in the autumn of 1879, of forty-two new double stars with a 6-inch achromatic, gave hopes since fully realised of a brilliant future for the Lick establishment. Its advantages are shared, as Professor Holden desired them to be, by the whole astronomical world.[1641] A sort of appellate jurisdiction was at once accorded to the great equatoreal, and more than one disputed point has been satisfactorily settled by recourse to it.

Its performances, considered both as to quality and kind, are unlikely to be improved upon by merely outbidding it in size, unless the care expended upon the selection of its site be imitated. Professor Pickering thus showed his customary prudence in reserving his efforts to procure a great telescope until Harvard College owned a dependent observatory where it could be employed to advantage. This was found by Mr. W. H. Pickering, after many experiments in Colorado, California, and Peru, at Arequipa, on a slope of the Andes, 8,000 feet above the sea-level. Here the post provided for by the "Boyden Fund" was established in 1891, under ideal meteorological conditions. Temperature preserves a "golden mean"; the barometer is almost absolutely steady; the yearly rainfall amounts to no more than three or four inches. No wonder, then, that the "seeing" there is of the extraordinary excellence attested by Mr. Pickering's observations. In the absence of bright moonlight, he tells us,[1642] eleven Pleiades can always be counted; the Andromeda nebula appears to the naked eye conspicuously bright, and larger than the full moon; third magnitude stars have been followed to their disappearance at the true horizon; the zodiacal light spans the heavens as a complete arch, the "Gegenschein" forming a regular part of the scenery of the heavens. Corresponding telescopic facilities are enjoyed. The chief instrument at the station, a 13-inch equatoreal by Clark, shows the fainter parts of the Orion nebula, photographed at Harvard College in 1887, by which the dimensions given to it in Bond's drawing are doubled; stars are at times seen encircled by half a dozen immovable diffraction rings, up to twelve of which have been counted round α Centauri; while on many occasions no available increase of magnifying power availed to bring out any wavering in the limbs of the planets. Moreover, the series of fine nights is nearly unbroken from March to November.

The facilities thus offered for continuous photographic research rendered feasible Professor Bailey's amazing discovery of variable star-clusters. They belong exclusively to the "globular" class, and the peculiarity is most strikingly apparent in the groups known as ο Centauri, and Messier 3, 5, and 15. A large number of their minute components run through perfectly definite cycles of change in periods usually of a few hours.[1643] Altogether, about 500 "cluster-variables" have been recorded since 1895. It should be mentioned that Mr. David Packer and Dr. Common discerned, about 1890, some premonitory symptoms of light-fluctuation among the crowded stars of Messier 5.[1644] With the Bruce telescope, a photographic doublet 24 inches in diameter, a store of 5,686 negatives was collected at Arequipa between 1896 and 1901. Some were exposed directly, others with the intervention of a prism; and all are available for important purposes of detection or investigation.

Vapours and air-currents do not alone embarrass the use of giant telescopes. Mechanical difficulties also oppose a formidable barrier to much further growth in size. But what seems a barrier often proves to be only a fresh starting-point; and signs are not wanting that it may be found so in this case. It is possible that the monumental domes and huge movable tubes of our present observatories will, in a few decades, be as much things of the past as Huygens's "aerial" telescopes. It is certain that the thin edge of the wedge of innovation has been driven into the old plan of equatoreal mounting.

M. Loewy, the present director of the Paris Observatory, proposed to Delaunay in 1871 the direction of a telescope on a novel system. The design seemed feasible, and was adopted; but the death of Delaunay and the other untoward circumstances of the time interrupted its execution. Its resumption, after some years, was rendered possible by M. Bischoffsheim's gift of 25,000 francs for expenses, and the *coudé* or "bent" equatoreal has been, since 1882, one of the leading instruments at the Paris establishment.

Its principle is briefly this: The telescope is, as it were, its own polar axis. The anterior part of the tube is supported at both ends, and is thus fixed in a direction pointing towards the pole, with only the power of twisting axially. The posterior section is joined on to it at right angles, and presents the object-glass, accordingly, to the celestial equator, in the plane of which it revolves. Stars in any other part of the heavens have their beams reflected upon the object-glass by means of a plane rotating mirror placed in front of it. The observer, meanwhile, is looking steadfastly down the bent tube towards the invisible *southern* pole. He would naturally see nothing whatever were it not that a second plane mirror is fixed at the "elbow" of the instrument, so as to send the rays which have traversed the object-glass to his eye. He never needs to move from his place. He watches the stars, seated in an arm-chair in a warm room, with as perfect convenience as if he were examining the seeds of a fungus with a microscope. Nor is this a mere gain of personal ease. The abolition of hardship includes a vast accession of power.[1645]

Among other advantages of this method of construction are, first, that of added stability, the motion given to the ordinary equatoreal being transferred, in part, to an auxiliary mirror. Next, that of increased focal length. The fixed part of the tube can be made almost indefinitely long without inconvenience, and with enormous advantage to the optical qualities of a large instrument. Finally, the costly and unmanageable cupola is got rid of, a mere shed serving all purposes of protection required for the "coudé."

The desirability of some such change as that which M. Loewy has realised has been felt by others. Professor Pickering sketched, in 1881, a plan for fixing large refractors in a permanently horizontal position, and reflecting into them, by means of a shifting mirror, the objects desired to be observed.[1646] The observations for his photometric catalogues are, in fact, made with a "broken transit," in which the line of sight remains permanently horizontal, whatever the altitude of the star examined. Sir Howard Grubb, moreover, set up, in 1882, a kind of siderostat at the Crawford Observatory, Cork. In a paper read before the Royal Society, January 21, 1884, he proposed to carry out the principle on a more extended scale;[1647] and shortly afterwards undertook its application to a telescope 18 inches in aperture for the Armagh Observatory.[1648] The chief honours, however, remain to the Paris inventor. None of the prognosticated causes of failure have proved effective. The loss of light from the double reflection is insignificant. The menaced deformation of images is, through the exquisite skill of the MM. Henry in producing plane mirrors of all but absolute perfection, quite imperceptible. The definition was admitted to be singularly good. Sir David Gill stated in 1884 that he had never measured a double star so easily as he did γ Leonis by its means.[1649] Sir Norman Lockyer pronounced it to be “one of the instruments of the future”; and the principle of its construction was immediately adopted by the directors of the Besançon and Algiers Observatories, as well as for a 17-inch telescope destined for a new observatory at Buenos Ayres. At Paris, it has since been carried out on a larger scale. A “coudé,” of 23-1/2 inches aperture and 62 feet focal length was in 1890 installed at the National Observatory, and has served M. Loewy for his ingenious studies on refraction and aberration—above all, for taking the magnificent plates of his lunar atlas. The “bent” form is capable of being, but has not yet been, adapted to reflectors.[1650]

The “cœlostat,” in the form given to it by Professor Turner, has proved an invaluable adjunct to eclipse-equipments. It consists essentially of a mirror rotating in forty-eight hours on an axis in its own plane, and parallel to the earth’s axis. In the field of a telescope kept rigidly pointed towards such a mirror, stars appear immovably fixed. The employment of long-focus lenses for coronal photography is thus facilitated, and the size of the image is proportional to the length of the focus. Professor Barnard, accordingly, depicted the totality of 1900 with a horizontal telescope 61-1/2 feet long, fed by a mirror 18 inches across, the diameter of the moon on his plates being 7 inches. The largest siderostat in the world is the Paris 50-inch refractor, which formed the chief attraction of the Palais d’Optique at the Exhibition of 1900. It has a focal length of nearly 200 feet, and can be used either for photographic or for visual purposes.

Celestial photography has not reached its grand climacteric; yet its earliest beginnings already seem centuries behind its present performances. The details of its gradual yet rapid improvement are of too technical a nature to find a place in these pages. Suffice it to say that the “dry-plate” process, with which such wonderful results have been obtained, appears to have been first made available by Sir William Huggins in photographing the spectrum of Vega in 1876, and was then successively adopted by Common, Draper, and Janssen. Nor should Captain Abney’s remarkable extension of the powers of the camera be left unnoticed. He began his experiments on the chemical action of red and infra-red rays in 1874, and at length succeeded in obtaining a substance—the “blue” bromide of silver—highly sensitive to these slower vibrations of light. With its aid he explored a vast, unknown, and for ever invisible region of the solar spectrum, presenting to the Royal Society, December 5, 1879,[1651] a detailed map of its infra-red portion (wave-lengths 7,600 to 10,750), from which valuable inferences may yet be derived as to the condition of the various kinds of matter ignited in the solar atmosphere. Upon plates rendered “orthochromatic” by staining with alizarine, or other dye-stuffs, the whole visible spectrum can now be photographed; but those with their maximum of sensitiveness near G are found preferable, except where the results of light-analysis are sought to be completely recorded. And since photographic refractors are corrected for the blue rays, exposures with them of orthochromatic surfaces would be entirely futile.

The chemical plate has two advantages over the human retina:[1652] First, it is sensitive to rays which are utterly powerless to produce any visual effect; next, it can accumulate impression almost indefinitely, while from the retina they fade after one-tenth part of a second, leaving it a continually renewed *tabula rasa*.

It is, accordingly, quite possible to photograph objects so faint as to be altogether beyond the power of any telescope to reveal—witness the chemical disclosure of the invisible nebula encircling Nova Persei—and we may thus eventually learn whether a blank space in the sky truly represents the end of the stellar universe in that direction, or whether farther and farther worlds roll and shine beyond, veiled in the obscurity of immeasurable distance.

Of many ingenious improvements in spectroscopic appliances the most fundamentally important relate to what are known as "gratings." These are very finely striated surfaces, by which light-waves are brought to interfere, and are thus sifted out, strictly according to their different lengths, into "normal" spectra. Since no universally valid measures can be made in any others, their production is quite indispensable to spectroscopic science. Fraunhofer, who initiated the study of the diffraction spectrum, used a real grating of very fine wires: but rulings on glass were adopted by his successors, and were by Nobert executed with such consummate skill that a single square inch of surface was made to contain 100,000 hand-drawn lines. Such rare and costly triumphs of art, however, found their way into very few hands, and practical availability was first given to this kind of instrument by the inventiveness and mechanical dexterity of two American investigators. Both Rutherfurd's and Rowland's gratings are machine-ruled, and reflect instead of transmitting the rays they analyse; but Rowland's present to them a very much larger diffractive surface, and consequently possess a higher resolving power. The first preliminary to his improvements was the production, in 1882, of a faultless screw, those previously in use having been the inevitable source of periodical errors in striation, giving, in their turn, ghost-lines as subjects of spectroscopic study.[1653] Their abolition was not one of Rowland's least achievements. With his perfected machine a metallic area of 6-1/4 by 4-1/4 inches can be ruled with exquisite accuracy to almost any degree of fineness; he considered, however, 43,000 lines to the inch to be the limit of usefulness.[1654] The ruled surface is, moreover, concave, and hence brings the spectrum to a focus without a telescope. A slit and an eye-piece are alone needed to view it, and absorption of light by glass lenses is obviated—an advantage especially sensible in dealing with the ultra- or infra-visible rays.

The high qualities of Rowland's great photographic map of the solar spectrum were thus based upon his previous improvement of the instrumental means used in its execution. The amount of detail shown in it is illustrated by the appearance on the negatives of 150 lines between H and K; and many lines depict themselves as double which, until examined with a concave grating, had passed for one and indivisible. A corresponding hand-drawing, for which M. Thollon received in 1886 the Lalande Prize, exhibits, not the diffractive, but the prismatic spectrum as obtained with bisulphide of carbon prisms of large dispersive power. About one-third of the visible gamut of the solar radiations (A to *b*) is covered by it; it includes 3,200 lines, and is over ten metres long.[1655] The grating is an expensive tool in the way of light. Where there is none to spare, its advantages must be foregone. They could not, accordingly, be turned to account in stellar spectroscopy until the Lick telescope was at hand to supply more abundant material for research. By the use thus made possible of Rowland's gratings, Professor Keeler was able to apply enormous dispersion to the rays of stars and nebulæ, and so to attain a previously unheard-of degree of accuracy in their measurement. His memorable detection of nebular movement in line of sight ensued as a consequence. Professor Campbell, his successor, has since obtained, by the same means, the first satisfactory photographs of stellar diffraction-spectra.

The means at the disposal of astronomers have not multiplied faster than the tasks imposed upon them. Looking back to the year 1800, we cannot fail to be astonished at the change. The comparatively simple and serene science of the heavenly bodies known to our predecessors, almost perfect so far as it went, incurious of what lay beyond its grasp, has developed into a body of manifold powers and parts, each with its separate mode and means of growth, full of strong vitality, but animated by a restless and unsatisfied spirit, haunted by the sense of problems unsolved, and tormented by conscious impotence to sound the immensities it perpetually confronts.

Knowledge might be said, when the *Mécanique Céleste* issued from the press, to be bounded by the solar system; but even the solar system presented itself under an aspect strangely different from what it now wears. It consisted of the sun, seven planets, and twice as many satellites, all circling harmoniously in obedience to a universal law, by the compensating action of which the indefinite stability of their mutual relations was secured. The occasional incursion of a comet, or the periodical presence of a single such wanderer chained down from escape to outer space by planetary attraction, availed nothing to impair the symmetry of the majestic spectacle.

Now, not alone the ascertained limits of the system have been widened by a thousand millions of miles, with the addition of one more giant planet and seven satellites to the ancient classes of its members, but a complexity has been given to its constitution baffling description or thought. Five hundred circulating planetary bodies bridge the gap between Jupiter and Mars, the complete investigation of the movements of any one of which would overtask the energies of a lifetime. Meteorites, strangers, apparently, to the fundamental ordering of the solar household, swarm, nevertheless, by millions in every cranny of its space, returning at regular intervals like the comets so singularly associated with them, or sweeping across it with hyperbolic velocities, brought, perhaps, from some distant star. And each of these cosmical grains of dust has a theory far more complex than that of Jupiter; it bears within it the secret of its origin, and fulfils a function in the universe. The sun itself is no longer a semi-fabulous, fire-girt globe, but the vast scene of the play of forces as yet imperfectly known to us, offering a boundless field for the most arduous and inspiring researches. Among the planets the widest variety in physical habitudes is seen to prevail, and each is recognised as a world apart, inviting inquiries which, to be effective, must necessarily be special and detailed. Even our own moon threatens to break loose from the trammels of calculation, and commits "errors" which sap the very foundations of the lunar theory, and suggest the formidable necessity for its complete revision. Nay, the steadfast earth has forfeited the implicit confidence placed in it as a time-keeper, and questions relating to the stability of the earth's axis and the constancy of the earth's rate of rotation are among those which it behoves the future to answer. Everywhere there is multiformity and change, stimulating a curiosity which the rapid development of methods of research offers the possibility of at least partially gratifying.

Outside the solar system, the problems which demand a practical solution are virtually infinite in number and extent. And these have all arisen and crowded upon our thoughts within less than a hundred years. For sidereal science became a recognised branch of astronomy only through Herschel's discovery of the revolutions of double stars in 1802. Yet already it may be, and has been called, "the astronomy of the future," so rapidly has the development of a keen and universal interest attended and stimulated the growth of power to investigate this sublime subject. What has been done is little—is scarcely a beginning; yet it is much in comparison with the total blank of a century past. And our knowledge will, we are easily persuaded, appear in turn the merest ignorance to those who come after us. Yet it is not to be despised, since by it we reach up groping fingers to touch the hem of the garment of the Most High.

APPENDIX

TABLE I

CHRONOLOGY, 1774-1893

1774, March 4	Herschel's first observation. Subject, the Orion Nebula.
1774	Sun-spots geometrically proved to be depressions by Wilson.
1774	First experimental determination of the earth's mean density by Maskelyne.
1781, March 13	Discovery of Uranus.
1782	Herschel's first Catalogue of Double Stars.
1783	Herschel's first investigation of the sun's movement in space.
1783	Goodricke's discovery of Algol's law of variation.
1784	Analogy between Mars and the Earth pointed out by Herschel.
1784	Construction of the Heavens investigated by Herschel's method of star-gauging. "Cloven-disc" plan of the Milky Way.
1784	Discovery of binary stars anticipated by Michell.
1786	Herschel's first Catalogue of Nebulæ.
1787, Jan. 11	Discovery by Herschel of two Uranian moons (Oberon and Titania).
1787, Nov. 19	Acceleration of the moon explained by Laplace.
1789	Herschel's second Catalogue of Nebulæ, and classification by age of these objects.
1789	Completion of Herschel's forty-foot reflector.
1789, Aug. 28 and Sept. 17	His discovery with it of the two inner Saturnian satellites.
1789	Repeating-circle invented by Borda.
1789	Five-foot circle constructed by Ramsden for Piazzi.
1790	Maskelyne's Catalogue of thirty-six fundamental stars.
1791	Herschel propounds the hypothesis of a fluid constitution for nebulæ.
1792	Atmospheric refraction in Venus announced by Schröter.
1794	Rotation-period of Saturn fixed by Herschel at 10h. 16m.
1795	Herschel's theory of the solar constitution.
1796	Herschel's first measures of comparative stellar brightness
1796	Laplace's Nebular Hypothesis published in *Exposition du Système du Monde*.
1797	Publication of Olbers's method of computing cometary orbits.
1798	Retrograde motions of Uranian satellites detected by Herschel.
1799	Publication of first two volumes of *Mécanique Céleste*.
1799, May 7	Transit of Mercury observed by Schröter.
1799, Nov. 12	Star-shower observed by Humboldt at Cumana.
1800	*Monatliche Correspondenz* started by Von Zach.
1800	Invisible heat-rays detected in the solar spectrum by Herschel.
1801, Jan. 1	Discovery of Ceres by Piazzi.
1801	Publication of Lalande's *Histoire Céleste*.
1801	Investigation by Herschel of solar emissive variability in connection with spot-development.
1802, March 28	Discovery of Pallas by Olbers.
1802	Herschel's third Catalogue of Nebulæ.
1802	Herschel's discovery of binary stars.
1802	Marks of clustering in the Milky Way noted by Herschel.
1802	Wollaston records seven dark lines in the solar spectrum.
1802, Nov. 9	Transit of Mercury observed by Herschel.
1804, Sept. 2	Transit of Mercury observed by Herschel.
1804	Foundation of Optical Institute at Munich.
1805	Herschel's second determination of the solar apex.

1807, March 29	Discovery of Vesta by Olbers.
1811	Herschel’s theory of the development of stars from nebulæ.
1811, Feb. 9	Death of Maskelyne. Pond appointed to succeed him as Astronomer-Royal.
1811, Sept. 12	Perihelion passage of great comet.
1814	Herschel demonstrates the irregular distribution of stars in space.
1815	Fraunhofer maps 324 dark lines in the solar spectrum.
1818	Publication of Bessel’s *Fundamenta Astronomiæ*.
1819	Recognition by Encke of the first short-period comet.
1819, June 26	Passage of the earth through the tail of a comet.
1820	Foundation of the Royal Astronomical Society.
1821	Foundation of Paramatta Observatory.
1821, September	First number of *Astronomische Nachrichten*.
1822, May 24	First calculated return of Encke’s comet.
1822, August 25	Death of Herschel.
1823	Bessel introduces the correction of observations for personal equation.
1823	Fraunhofer examines the spectra of fixed stars.
1824	Distance of the sun concluded by Encke to be 95-1/4 million miles.
1824	Publication of Lohrmann’s Lunar Chart.
1824	Dorpat refractor mounted equatoreally.
1826	Commencement of Schwabe’s observations of sun-spots.
1826, Feb. 27	Biela’s discovery of a comet.
1827	Orbit of a binary star calculated by Savary.
1829	Completion of the Royal Observatory at the Cape of Good Hope.
1829	The Königsberg heliometer mounted.
1830	Publication of Bessel’s *Tabulæ Regiomontanæ*.
1832	Discovery by Brewster of “atmospheric lines” in the solar spectrum.
1833	Magnetic observatory established at Göttingen.
1833, Nov. 12, 13	Star-shower visible in North America.
1833	Completion of Sir J. Herschel’s survey of the northern heavens.
1834, Jan. 16	Sir J. Herschel’s landing at the Cape.
1835, September	Airy appointed Astronomer-Royal in succession to Pond.
1835, Nov. 16	Perihelion passage of Halley’s comet.
1837	Solar movement determined by Argelander.
1837	Bessel’s application of the heliometer to measurements of stellar parallax.
1837	Publication of Beer and Mädler’s *Der Mond*.
1837, Dec. 16	Outburst of η Carinæ observed by Sir J. Herschel.
1837	Thermal power of the sun measured by Herschel and Pouillet.
1838	Parallax of 61 Cygni determined by Bessel.
1839, Jan. 9	Parallax of α Centauri announced by Henderson.
1839	Completion of Pulkowa Observatory.
1839	Solidity of the earth concluded by Hopkins.
1840, March 2	Death of Olbers.
1840	First attempt to photograph the moon by J. W. Draper.
1842	Doppler enounces principle of colour-change by motion.
1842	Conclusion of Baily’s experiments in weighing the Earth.
1842, July 8	Total solar eclipse. Corona and prominences observed by Airy, Baily, Arago, and Struve.
1843, Feb. 27	Perihelion-passage of great comet.
1845, February	Completion of Parsonstown reflector.
1845, April	Discovery with it of spiral nebulæ.
1845, April 2	Daguerreotype of the sun taken by Foucault and Fizeau.
1845, Oct. 21	Place of Neptune assigned by Adams.
1845, Dec. 8	Discovery of Astræa by Hencke.

1845, Dec. 29	Duplication of Biela’s comet observed at Yale College.
1846	Melloni’s detection of heating effects from moonlight.
1846, March 17	Death of Bessel.
1846, Sept. 23	Discovery of Neptune by Galle.
1846, Oct. 10	Neptune’s satellite discovered by Lassell.
1847	Publication of Sir J. Herschel’s *Results of Observations at the Cape of Good Hope*.
1847	Cyclonic theory of sun-spots stated by him.
1848	J. R. Mayer’s meteoric hypothesis of solar conservation.
1848	Motion-displacements of Fraunhofer lines adverted to by Fizeau.
1848, April 27	New Star in Ophiuchus observed by Hind.
1848, Sept. 19	Simultaneous discovery of Hyperion by Bond and Lassell.
1849	First experimental determination of the velocity of by Fizeau.
1848, April 27	New Star in Ophiuchus observed by Hind.
1848, Sept. 19	Simultaneous discovery of Hyperion by Bond and Lassell.
1849	First experimental determination of the velocity of light (Fizeau).
1850, July 17	Vega photographed at Harvard College.
1850, Nov. 15	Discovery by Bond of Saturn’s dusky ring.
1851	O. Struve’s first measurements of Saturn’s ring-system
1851, July 28	Total solar eclipse observed in Sweden.
1851, Oct. 24	Discovery by Lassell of two inner Uranian satellites.
1851	Schwabe’s discovery of sun-spot periodicity published by Humboldt.
1852, May 6	Coincidence of magnetic and sun-spot periods announced by Sabine.
1852, Oct. 11	Variable nebula in Taurus discovered by Hind.
1852	Lassell’s two-foot reflector transported to Malta.
1853	Adams shows Laplace’s explanation of the moon’s acceleration to be incomplete.
1854	Hansen infers from lunar theory a reduced value for the distance of the sun.
1854	Helmholtz’s “gravitation theory” of solar energy.
1856	Piazzi Smyth’s observations on the Peak of Teneriffe.
1857	Saturn’s rings shown by Clerk Maxwell to be of meteoric formation.
1857, April 27	Double-star photography initiated at Harvard College.
1858	Solar photography begun at Kew.
1858, Sept. 30	Perihelion of Donati’s comet.
1859	Spectrum analysis established by Kirchhoff and Bunsen.
1859	Carrington’s discovery of the compound nature of the sun’s rotation.
1859, Sept. 1	Luminous solar outburst and magnetic storm.
1859, Oct. 19	Merope nebula discovered by Tempel.
1859, Dec. 15	Chemical constitution of the sun described by Kirchhoff.
1860, Feb. 27	Discovery by Liais of a “double comet.”
1860, May 21	New star in Scorpio detected by Auwers.
1860, July 18	Total solar eclipse observed in Spain. Prominences shown by photography to be solar appendages.
1861, June 30	The earth involved in the tail of a great comet.
1861-1862	Kirchhoff’s map of the solar spectrum.
1862	Solar hydrogen-absorption recognised by Ångström.
1862, Jan. 31	Discovery by Alvan G. Clark of the companion of Sirius.
1862	Foucault determines the sun’s distance by the velocity of light.
1862	Opposition of Mars. Determination of solar parallax.
1862	Completion of *Bonner Durchmusterung*.
1863	Secchi’s classification of stellar spectra.
1863	Foundation of the German Astronomical Society.
1864, March 5	Rotation period of Mars determined by Kaiser.
1864	Huggins’s first results in stellar spectrum analysis.
1864, Aug. 5	Spectroscopic examination of Tempel’s comet by Donati shows it to be composed of glowing gas.
1864, Aug. 29	Discovery by Huggins of gaseous nebulæ.

1864	Value of 91,000,000 miles adopted for the sun’s distance.
1864	Croll’s explanation of glacial epochs.
1864, Nov. 23	Death of Struve.
1865, Jan. 4	Spectroscopic observation by Huggins of the occultation of ε Piscium.
1865, Jan. 16	Faye’s theory of the solar constitution.
1865	Kew results published.
1865	Zöllner argues for a high temperature in the great planets.
1866	Identity of the orbits of the August meteors and of comet 1862 iii. demonstrated by Schiaparelli.
1866	Delaunay explains lunar acceleration by a lengthening of the day through tidal friction.
1866, March 4	Spectroscopic study of the sun’s surface by Lockyer.
1866, March 12	New star in Corona Borealis detected by Birmingham.
1866, October	Schmidt announces the disappearance of the lunar crater Linné.
1866, Nov. 13	Meteoric shower visible in Europe.
1867	Period of November meteors determined by Adams.
1867, Aug. 29	Total solar eclipse. Minimum sun-spot type of corona observed by Grosch at Santiago.
1867	Discovery of gaseous stars in Cygnus by Wolf and Rayet.
1868, February	Principle of daylight spectroscopic visibility of prominences started by Huggins.
1868, Aug. 18	Great Indian eclipse. Spectrum of prominences observed.
1868, Aug. 19	Janssen’s first daylight view of a prominence.
1868, Oct. 26	Lockyer and Janssen independently announce their discovery of the spectroscopic method.
1868	Doppler’s principle applied by Huggins to measure stellar radial movements.
1868	Publication of Ångström’s map of the normal solar spectrum.
1868	Spectrum of Winnecke’s comet found by Huggins to agree with that of olefiant gas.
1869, Feb. 11	Tenuity of chromospheric gases inferred by Lockyer and Frankland.
1869, Feb. 13	Huggins observes a prominence with an “open slit.”
1869, Aug. 7	American eclipse. Detection of bright-line coronal spectrum.
1870	Mounting of Newall’s 25-inch achromatic at Gateshead.
1870	Proctor indicates the prevalence of drifting movements among the stars.
1870	A solar prominence photographed by Young.
1870, Dec. 22	Sicilian eclipse. Young discovers reversing layer.
1871, May 11	Death of Sir J. Herschel.
1871, June 9	Line-displacements due to solar rotation detected by Vogel.
1871, Dec. 12	Total eclipse visible in India. Janssen observes reflected Fraunhofer lines in spectrum of corona.
1872	Conclusion of a three years’ series of observations on lunar heat by Lord Rosse.
1872	Spectrum of Vega photographed by H. Draper.
1872	Faye’s cyclonic hypothesis of sun-spots.
1872	Young’s solar-spectroscopic observations at Mount Sherman.
1872	Cornu’s experiments on the velocity of light.
1872, Nov. 27	Meteoric shower connected with Biela’s comet.
1873	Determination of mean density of the earth by Cornu and Baille.
1873	Solar photographic work begun at Greenwich.
1873	Erection of 26-inch Washington refractor.
1874	Light-equation redetermined by Glasenapp.
1874	Vogel’s classification of stellar spectra.
1874, Dec. 8	Transit of Venus.
1876	Publication of Neison’s *The Moon*.
1876, Nov. 24	New star in Cygnus discovered by Schmidt.
1876	Spectrum of Vega photographed by Huggins. First use of dry gelatine plates in celestial photography.
1877, May 19	Klein observes a supposed new lunar crater (Hyginus N.).
1877	Measurement by Vogel of selective absorption in solar atmosphere.
1877, Aug. 16-17	Discovery of two satellites of Mars by Hall at Washington.

1877, Sept. 23	Death of Leverrier.
1877	Canals of Mars discovered by Schiaparelli.
1877	Opposition of Mars observed by Gill at Ascension. Solar parallax deduced = 8·78′.
1878, January	Stationary meteor-radiants described by Denning.
1878	Publication of Schmidt's *Charte der Gebirge des Mondes*.
1878	First observations of Great Red Spot on Jupiter.
1878	Conclusion of Newcomb's researches on the lunar theory.
1878, May 6	Transit of Mercury.
1878	Foundation of Selenographical Society.
1878, July 29	Total eclipse visible in America. Vast equatoreal extension of the corona.
1878, October	Completion of Potsdam Astrophysical Observatory.
1878, Dec. 12	Lockyer's theory of celestial dissociation communicated to the Royal Society.
1879	Michelson's experiments on the velocity of light.
1879	Publication of Gould's *Uranometria Argentina*.
1879, November	Observations of the spectra of sun-spots begun at South Kensington.
1879, Dec. 5	Abney's map of the infra-red solar spectrum presented to the Royal Society.
1879, Dec. 18	Ultra-violet spectra of white stars described by Huggins.
1879, Dec. 18	Communication of G. H. Darwin's researches into the early history of the moon.
1880, Jan. 31	Discovery at Cordoba of a great southern comet.
1880	Conditions of Algol's eclipses determined by Pickering.
1880	Pickering computes mass-brightness of binary stars.
1880, Sept. 30	Draper's photograph of the Orion nebula.
1880	The bolometer invented by Langley.
1881, Jan. 20	Communication of G. H. Darwin's researches into the effects of tidal friction on the evolution of the solar system.
1881	Langley's observations of atmospheric absorption on Mount Whitney.
1881, June 16	Perihelion of Tebbutt's comet.
1881, June 24	Its spectrum photographed by Huggins.
1881, June	Photographs of Tebbutt's comet by Janssen and Draper.
1881, Aug. 15	Retirement of Sir George Airy. Succeeded by Christie.
1881, Aug. 22	Perihelion of Schaeberle's comet.
1881	Publication of Stone's Cape Catalogue for 1880.
1881	Struve's second measures of Saturn's ring-system.
1882	Newcomb's determination of the velocity of light. Resulting solar parallax = 8·79′.
1882	Correction by Nyrén of Struve's constant of aberration.
1882, March 7	Spectrum of Orion nebula photographed by Huggins.
1882, May 17	Total solar eclipse observed at Sohag in Egypt.
1882, May 27	Sodium-rays observed at Dunecht in spectrum of Comet Wells.
1882, June 10	Perihelion of Comet Wells.
1882, Sept. 17	Perihelion of Great Comet. Daylight detection by Common. Transit observed at the Cape.
1882, Sept. 18	Iron lines identified in spectrum by Copeland and J. G. Lohse.
1882, September	Photographs of comet taken at the Cape Observatory, showing a background crowded with stars.
1882, Dec. 6	Transit of Venus.
1882	Duplication of Martian canals observed by Schiaparelli.
1882	Completion by Loewy at Paris of first equatoreal Coudé.
1882	Rigidity of the earth concluded from tidal observations by G. H. Darwin.
1882	Experiments by Huggins on photographing the corona without an eclipse.
1882	Publication of Holden's *Monograph of the Orion Nebula*.
1883, Jan. 30	Orion Nebula photographed by Common.
1883, May 6	Caroline Island eclipse.
1883, June 1	Great comet of 1882 observed from Cordoba at a distance from the earth of 470 million miles.
1883	Parallaxes of nine southern stars measured by Gill and Elkin.

1883	Catalogue of the spectra of 4,051 stars by Vogel.
1884, Jan. 25	Return to perihelion of Pons’s comet.
1884	Photometric Catalogue by Pickering of 4,260 stars.
1884	Publication of Gore’s Catalogue of Variable Stars.
1884	Publication of Faye’s *Origine du Monde*.
1884, Oct. 4	Eclipse of the moon. Heat-phases measured by Boeddicker at Parsonstown.
1884	Dunér’s Catalogue of Stars with Banded Spectra.
1884	Backlund’s researches into the movements of Encke’s comet.
1885, February	Langley measures the lunar heat-spectrum.
1885	Publication of *Uranometria Nova Oxoniensis*.
1885, Aug. 17	New star in Andromeda nebula discerned by Gully.
1885, Sept. 5	Thollon’s drawing of the solar spectrum presented to the Paris Academy.
1885, Sept. 9	Solar eclipse visible in New Zealand.
1885, Nov. 16	Photographic discovery by Paul and Prosper Henry of a nebula in the Pleiades.
1885, Nov. 27	Shower of Biela meteors.
1885	Thirty-inch achromatic mounted at Pulkowa.
1885	Publication of Rowland’s photographic map of the normal solar spectrum.
1885	Bakhuyzen’s determination of the rotation period of Mars.
1885	Stellar photographs by Paul and Prosper Henry.
1886, Jan. 26	Spectra of forty Pleiades simultaneously photographed at Harvard College.
1886, Feb. 5	First visual observation of the Maia nebula with Pulkowa 30-inch refractor.
1886, March	Photographs by the Henrys of the Pleiades, showing 2,326 stars with nebulæ intermixed.
1886, May	Photographic investigations of stellar parallax undertaken by Pritchard.
1886, May 6	Periodical changes in spectra of sun-spots announced by Pritchard.
1886, June 4	An international Photographic Congress proposed by Gill.
1886, Aug. 29	Total eclipse of the sun observed at Grenada.
1886, Oct. 1	Roberts’s photograph showing annular structure of the Andromeda nebula.
1886, Dec. 8	Roberts’s photograph of the Pleiades nebulosities.
1886	Solar heat-spectrum extended by Langley to below five microns.
1886, Dec. 28	Detection by Copeland of helium-ray in spectrum of the Orion nebula.
1886	Thirty-inch refractor mounted at Nice.
1886	Publication of Argentine General Catalogue.
1886	Completion of Auwers’s reduction of Bradley’s observations.
1886	Draper Memorial photographic work begun at Harvard College.
1886	Photographic detection at Harvard College of bright hydrogen lines in spectra of variables (Mira Ceti and U Orionis).
1887, Jan. 18	Discovery by Thome at Cordoba of a great comet belonging to the same group as the comet of 1882.
1887	Publication of Lockyer’s *Chemistry of the Sun*.
1887, April 16	Meeting at Paris of the International Astrophotographic Congress.
1887	Heliometric triangulation of the Pleiades by Elkin.
1887	L. Struve’s investigation of the sun’s motion, and redetermination of the constant of precession.
1887	Von Konkoly’s extension to 15° S. Dec. of Vogel’s spectroscopic Catalogue.
1887	Auwers’s investigation of the solar diameter.
1887	Publication of Schiaparelli’s Measures of Double Stars (1875-85).
1887, April 8	Death of Thollon at Nice.
1887, Aug. 19	Total eclipse of the sun. Shadow-path crossed Russia. Observations marred by bad weather.
1887, November	Langley’s researches on the temperature of the moon.
1887, Nov. 17	Lockyer’s *Researches on Meteorites* communicated to the Royal Society.
1887	Completion of 36-inch Lick refractor.
1888	Küstner’s detection of variations in the latitude of Berlin brought before the International Geodetic Association.
1888	Chandler’s first Catalogue of Variable Stars.

1888	Mean parallax of northern first magnitude stars determined by Elkin.
1888	Publication of Dreyer's *New General Catalogue* of 7,844 nebulæ.
1888	Vogel's first spectrographic determinations of stellar radial motion.
1888	Carbon absorption recognised in solar spectrum by Trowbridge and Hutchins.
1888, Jan. 28	Total eclipse of the moon. Heat-phases measured at Parsonstown.
1888, Feb. 5	Remarkable photograph of the Orion nebula spectrum taken at Tulse Hill.
1888, June 1	Activity of the Lick Observatory begun.
1888	Completion of Dr. Common's 5-foot reflector.
1888	Heliometric measures of Iris for solar parallax at the Cape, Newhaven (U.S.A.), and Leipsic.
1888	Loewy describes a comparative method of determining constant of aberration.
1888	Presentation of the Dunecht instrumental outfit to the nation by Lord Crawford. Copeland succeeds Piazzi Smyth as Astronomer-Royal for Scotland.
1888, Sept. 12	Death of R. A. Proctor.
1889	Photograph of the Orion nebula taken by W. H. Pickering, showing it to be the nucleus of a vast spiral.
1889	Discovery at a Harvard College of the first-known spectroscopic doubles, ζ Ursæ Majoris and β Aurigæ.
1889	Eclipses of Algol demonstrated spectrographically by Vogel.
1889	Completion of photographic work for the Southern Durchmusterung.
1889	Boeddicker's drawing of the Milky Way.
1889	Draper Memorial photographs of southern star-spectra taken in Peru.
1889	Pernter's experiments on scintillation from the Sonnblick.
1889	H. Struve's researches on Saturn's satellites.
1889	Harkness's investigation of the masses of Mercury, Venus, and the Earth.
1889	Heliometric measures of Victoria and Sappho at the Cape.
1889, Jan. 1	Total solar eclipse visible in California.
1889, Feb. 7	Foundation of the Astronomical Society of the Pacific.
1889, March	Investigation by Sir William and Lady Huggins of the spectrum of the Orion nebula.
1889, July-Aug.	First photographs of the Milky Way taken by Barnard.
1889, August 2	Observation by Barnard of four companions to Brooks's comet.
1889, Nov. 1	Passage of Japetus behind Saturn's dusky ring observed by Barnard.
1889, December	Schiaparelli announces synchronous rotation and revolution of Mercury.
1889, Dec. 22	Total eclipse of the sun visible in Guiana. Death of Father Perry, December 27.
1889	Spectrum of Uranus investigated visually by Keeler, photographically by Huggins.
1890	Long-exposure photographs of ring-nebula in Lyra.
1890	Determinations of the solar translation by L. Boss and O. Stumpe.
1890	Schiaparelli finds for Venus an identical period of rotation and revolution.
1890	Publication of Thollon's map of the solar spectrum.
1890	Bigelow's mathematical theory of coronal structures.
1890	Foundation of the British Astronomical Association.
1890	Measurements by Keeler at Lick of nebular radial movements.
1890	Janssen's ascent of Mont Blanc, by which he ascertained the purely terrestrial origin of the oxygen-absorption in the solar spectrum.
1890	Newcomb's discussion of the transits of Venus of 1761 and 1769.
1890	Spiral structure of Magellanic Clouds displayed in photographs taken by H. C. Russell of Sydney.
1890	Publication of the Draper Catalogue of Stellar Spectra.
1890, April 24	Spica announced by Vogel to be a spectroscopic binary.
1890, June	Gore's Catalogue of computed Binaries.
1890, November	Study by Sir William and Lady Huggins of the spectra of Wolf and Rayet's stars in Cygnus.
1890, November	Discovery by Barnard of a close nebulous companion to Merope in the Pleiades.
1890, November	McClean Spectrographs of the High and Low Sun.
1891	Capture-theory of comets developed by Callandreau, Tisserand, and Newton.
1891	Dunér's spectroscopic researches on the sun's rotation.

1891	Preponderance of Sirian stars in the Milky Way concluded by Pickering, Gill, and Kapteyn.
1891	Detection by Mrs. Fleming of spectral variations corresponding to light-changes in β Lyræ.
1891	Establishment of the Harvard College Station at Arequipa in Peru (height 8,000 feet).
1891	Variations of latitude investigated by Chandler.
1891	Prominence-photography set on foot by Hale at Chicago and Deslandres at Paris.
1891	Schmidt’s Theory of Refraction in the Sun.
1891, April	Meeting at Paris of the Permanent Committee for the Photographic Charting of the Heavens.
1891, May 9	Transit of Mercury.
1891, Aug. 19	Presidential Address by Huggins at the Cardiff Meeting of the British Association.
1891, Dec. 10	Nova Aurigæ photographed at Harvard College.
1891, Dec. 20	Photographic maximum of Nova Aurigæ.
1891, Dec. 22	First photographic discovery of a minor planet by Max Wolf at Heidelberg.
1892	Commencement of international photographic charting work.
1892	Photographic determination by Scheiner of 833 stars in the Hercules Cluster (M 13).
1892	Publication of Vogel’s spectrographic determinations for fifty-one stars.
1892	Publication of Pritchard’s photographic parallaxes.
1892, Jan. 2	Death of Sir George Airy.
1892, Jan. 21	Death of Professor Adams.
1892, Feb. 1	Announcement by Anderson of the outburst of a new star in Auriga.
1892, Feb. 5	Appearance of the largest sun-spot ever photographed at Greenwich.
1892, March	Photograph of Argo nebula taken by Gill in twelve hours.
1892, March 6	Discovery of a bright comet by Swift.
1892, June 29	Death of Admiral Mouchez. Succeeded by Tisserand as director of the National Observatory, Paris.
1892, Aug. 4	Favourable Opposition of Mars.
1892, Aug. 17	Rediscovery at Lick of Nova Aurigæ.
1892, Sept. 9	Discovery by Barnard of Jupiter’s inner satellite.
1892, Oct. 12	First photographic discovery of a comet by Barnard.
1892, Nov. 6	Discovery of Holmes’s comet.
1892, Nov. 23	Shower of Andromede meteors visible in America.
1892	Poynting’s Determination of the Earth’s Mean Density.
1892	Dunér’s Investigation of the System of Y Cygni.
1892	Photographic investigation by Deslandres of the spectra of prominences.
1892	Photographs of the sun with faculæ and chromospheric surroundings taken by Hale with a single exposure.
1892	Investigation by T. J. J. See of the ancient colour of Sirius.
1892	Publication of T. J. J. See’s Thesis on the Evolution of Binary Systems.
1892	Chandler’s theory of Algol’s inequalities.
1892	Nebula in Cygnus photographically discovered by Max Wolf.
1893, Jan. 28	Kapteyn’s investigation of the structure of the universe.
1893, March 10	Gill announces his results from the Opposition of Victoria, among them a solar parallax = 8·809′.
1893, April 16	Total solar eclipse observed in South America and West Africa.
1893	Publication of Kruger’s *Catalog der Farbigen Sterne*.
1893	Conclusion of Boys’s series of Experiments on the Density of the Earth.
1893	Publication of *Cordoba Durchmusterung*, vol. i.
1893	Fabry shows comets to be dependents of the Solar System.
1893	Publication of Easton’s *Voie Lactée*.
1893	Campbell detects bright Hα in γ Argûs and Alcyone.
1893	Nova Normæ photographed July 10; discovered on plates, October 26.
1893, May 28	Death of Professor Pritchard.
1893, July 27	Installation of 28-inch refractor at the Royal Observatory, Greenwich.
1893, December	Exterior nebulosities of Pleiades photographed by Barnard.
1893, Dec. 6	Death of Rudolf Wolf.
1894, January	Sun-spot maximum.

1894	Publication of Potsdam *Photometric Durchmusterung*, part i.
1894	Publication of Roberts's *Celestial Photographs*, vol. i.
1894	Wilson and Gray's determination of the sun's temperature.
1894	Barnard's micrometric measures of asteroids.
1894	McClean's gift of an astrophysical outfit to the Cape Observatory.
1894	Establishment of the Lowell Observatory at Flagstaff, Arizona.
1894	Taylor's triple achromatic objective described.
1894, April 3	Discovery of Gale's Comet.
1894	Sampson's investigation of the sun's rotation.
1894, Oct. 20	Favourable opposition of Mars.
1894, Nov. 11	Transit of Mercury.
1894, December	Howlett impugns the Wilsonian theory of sun-spots.
1894, Dec. 14	Death of A. Cowper Ranyard.
1895	Publication of Newcomb's *Astronomical Constants*.
1895	Bailey's Photometric Catalogue of 7,922 Southern Stars.
1895	Bailey's photographic discovery of variable star clusters.
1895	Publication of E. W. Brown's *Lunar Theory*.
1895	Tisserand's theory of the inequalities of Algol.
1895	Stratonoff's determination of the sun's rotation from photographs of faculæ.
1895	Binary character of η Aquilæ spectroscopically recognised by Bélopolsky.
1895	Presentation of the Crossley reflector to the Lick Observatory.
1895, March 23	Great nebula in Ophiuchus discovered photographically by Barnard.
1895, March 25	Ramsay's capture of Helium.
1895, April	Constitution of Saturn's rings spectrographically demonstrated by Keeler.
1895	Binary character of δ Cephei spectroscopically detected by Bélopolsky.
1895, June 11	Death of Daniel Kirkwood.
1895, July 7	Death of F. W. G. Spörer.
1895, October	Nova Carinæ spectrographically discovered by Mrs. Fleming.
1895, Dec. 12	Nova Centauri spectrographically discovered by Mrs. Fleming.
1895, Dec. 28	Death of John Russell Hind.
1896	Gill's Report on the Geodetic Survey of South Africa.
1896	Appearance of Loewy's Photographic Atlas of the Moon, part i.
1896, January	Fessenden's electrostatic theory of comets.
1896	Chandler's Third Catalogue of Variable Stars.
1896	Publication of Lick Observatory Photographic Atlas of the Moon, part i.
1896, February	Effects of pressure on wave-length described by Humphreys and Mohler.
1896, April 5	Opening of new Scottish Royal Observatory on Blackford Hill, Edinburgh.
1896, April	Pickering's photometric determinations of light curves of variable stars.
1896	One of the stars of Castor spectroscopically resolved into two by Bélopolsky.
1896, May	Third Astrographic Chart Conference at Paris.
1896, Aug. 9	Total eclipse of the sun visible in Novaya Zemlya. Reversing layer photographed by Shackleton.
1896, Aug. 30	Death of Hubert A. Newton.
1896, Sept. 18	Death of Hippolyte Fizeau.
1896, Oct. 20	Death of F. Tisserand. Succeeded by Maurice Loewy.
1896, Nov. 13	Detection by Schaeberle of Procyon's missing satellite.
1896, Nov. 26	Death of Benjamin Apthorp Gould.
1896, November	Second series of hydrogen-lines discovered by Pickering in stellar spectra.
1896, December	Zeeman's discovery of spectral modifications through magnetic influence.
1896, December	Oxygen-absorption identified in the sun by Runge and Paschen.
1896	Study of lunar formations by Loewy and Puiseux.
1896	Mounting of the Mills spectrograph at the Lick Observatory.
1897	Installation at Greenwich of the Thompson 26-inch photographic refractor.
1897	Publication of Miss Maury's Discussion of the Photographed Spectra of 681 Stars.

1897	Callandreau's researches on cometary disaggregation.
1897	Braun's determination of the earth's mean density.
1897	Tenuity of calcium vapour in chromosphere demonstrated spectroscopically by Sir William and Lady Huggins.
1897	Completion at the Cape Observatory of McClean's spectrographic survey of the heavens.
1897	Twenty-one Wolf-Rayet stars found by Mrs. Fleming in Magellanic Cloud.
1897	Percival Lowell's *New Observations on the Planet Mercury* presented to the American Academy.
1897, April 8	McClean recognises oxygen-absorption in helium stars.
1897, May 9	Death of E. J. Stone, Radcliffe Observer.
1897, June 10	Death of Alvan G. Clark.
1897, June 18	Spectrum of a meteor photographed at Arequipa.
1897, Oct. 21	Inauguration of the Yerkes Observatory.
1897	Rabourdin's photographs of nebulæ with the Meudon reflector.
1897	Dr. See's discoveries of Southern double stars with the Lowell 24-inch refractor.
1898, Jan. 22	Total eclipse of the sun visible in India.
1898, February	Binary character of ζ Geminorum ascertained spectroscopically by Bélopolsky.
1898	Star with proper motion of nearly 9′ discovered by Innes and Kapteyn from the Cape Durchmusterung plates.
1898, March 8	Nova Sagittarii photographed on Draper Memorial plates.
1898, June 20	Opening of Grand-ducal Observatory at Königsstuhl, Heidelberg.
1898	Keeler succeeds Holden as Director of the Lick Observatory.
1898	Bruno Peter's results in stellar parallax.
1898	Lewis Swift's discoveries of nebulæ at Echo California.
1898	Hale's photographic investigation of carbon stars.
1898, Aug. 14	Discovery of Eros by Witt.
1898	Flint's investigations of stellar parallax by meridian differences.
1898	Easton's spiral theory of the Milky Way.
1898	Seeliger's research on star distribution.
1898, October	Multiple hydrogen-bands observed by Campbell in Mira Ceti.
1898, November	Orbit of a Leonid meteor photographically determined by Elkin.
1899	Publication of Potsdam *Photometric Durchmusterung*, part ii.
1899	Innes's *Reference Catalogue of Southern Double Stars*.
1899	Keeler's photographs of nebulæ with the Crossley reflector and generalization of their spiral character.
1899, January	Spectrum of Andromeda nebula photographed by Scheiner.
1899, April	Photographic discovery of Nova Aquilæ by Mrs. Fleming.
1899, Aug. 26	Installation of 31-inch photographic refractor at Potsdam.
1899	Campbell's detection of Polaris as spectroscopically triple.
1899, October	Duplicate discovery by Campbell and Newall of Capella as a spectroscopic binary.
1899, Nov. 15	Failure of the Leonids. Deflection of the stream predicted by Johnstone Stoney and Downing.
1899, December	Publication of Sir William and Lady Huggins's *Atlas of Representative Stellar Spectra*.
1899	Thirty-two-inch photographic refractor mounted at Meudon.
1899	Issue of first volume of Potsdam measures of international catalogue plates.
1900, Jan. 27	Kapteyn's determination of the apex of solar motion.
1900	Chase's measures for parallax of swiftly-moving stars.
1900	Publication of Gill's *Researches on Stellar Parallax*.
1900	Kapteyn proposes a method for a stellar parallax Durchmusterung, and gives specimen results for 248 stars.
1900	Burnham's general catalogue of 1,290 double stars.
1900	Publication of the concluding volume of the *Cape Photographic Durchmusterung*.
1900, May 28	Spanish-American total eclipse of the sun.
1900, July	International Conference at Paris. Co-operation arranged of fifty-eight observatories in measures of Eros for solar parallax.

1900	Horizontal refractor, of 50 inches aperture, 197 feet focus, installed in Paris Exhibition.
1900, Aug. 12	Death of Professor Keeler. Succeeded by Campbell in direction of Lick Observatory.
1900, November	Opposition of Eros.
1900	Publication of Roberts's *Celestial Photographs*, vol. ii.
1900	Complete publication of Langley's researches on infra-red spectrum.
1900	Printing begun of Paris section of International Photographic Catalogue.
1901, Feb. 22	Nova Persei discovered by Anderson.
1901, February	Variability of Eros announced by Oppolzer.
1901, April 23	Apparition of a great comet at the Cape.
1901	Publication of Pickering's *Photometric Durchmusterung*.
1901	Miss Cannon's discussion of the spectra of 1,122 Southern stars.
1901	Kapteyn's investigation of mean stellar parallax.
1901	Campbell's determination of the sun's velocity.
1901	Porter's research on the solar motion in space.
1901	Bigelow's magnetic theory of the solar corona.
1901	Hussey's measurements of the Pulkowa double stars.
1901	Radial velocities of the components of δ Equulei measured at Lick.
1901, April 16	Death of Henry A. Rowland.
1901, June	Nebular spectrum derived from Nova Persei.
1901, Aug. 23	Nebula near Nova Persei photographed by Max Wolf.
1901, Sept. 20	The same exhibited in spiral form on a plate taken by Ritchey at the Yerkes Observatory.
1901, Nov. 8	Photograph taken by Perrine with the Crossley reflector showed nebula in course of rapid change.
1901, Sept. 19	Unveiling of the McClean "Victoria" telescope at the Royal Observatory, Cape of Good Hope.
1901	Sun-spot minimum.

TABLE II

CHEMICAL ELEMENTS IN THE SUN (ROWLAND, 1891).

Arranged according to the number of their representative Lines in the Solar Spectrum.

Iron (2000+).	Neodymium.	Cadmium.
Nickel.	Lanthanum.	Rhodium.
Titanium.	Yttrium.	Erbium.
Manganese.	Niobium.	Zinc.
Chromium.	Molybdenum.	Copper (2).
Cobalt.	Palladium.	Silver (2).
Carbon (200+).	Magnesium (20+).	Glucinum (2).
Vanadium.	Sodium (11).	Germanium.
Zirconium.	Silicon.	Tin.
Cerium.	Strontium.	Lead (1).
Calcium (75+).	Barium.	Potassium (1).
Scandium.	Aluminium (4).	

TABLE III

EPOCHS OF SUN-SPOT MAXIMUM AND MINIMUM FROM 1610 TO 1901.

Minima.	Maxima.		Minima.	Maxima.		Minima.	Maxima.
1610·8	1615·5		1712·0	1718·2		1810·6	1816·4
1619·0	1626·0		1723·5	1727·5		1823·3	1829·9
1634·0	1639·5		1734·0	1738·7		1833·9	1837·2
1645·0	1649·0		1745·0	1750·3		1843·5	1848·1
1655·0	1660·0		1755·2	1761·5		1856·0	1860·1
1666·0	1675·0		1766·5	1769·7		1867·2	1870·6
1679·5	1685·0		1775·5	1778·4		1878·9	1884·0
1689·5	1693·0		1784·7	1788·1		1890·2	1894·0
1698·9	1705·5		1798·3	1804·2		1901·9	

TABLE IV.

MOVEMENTS OF SUN AND STARS.

1. Translation of Solar System.

Apex of Movement.		Authority.	Date.
R. A.	Dec.		
277° 30′	+ 35°	Newcomb	1898
273° 36′	+ 29° 30′	Kapteyn	1901
279°	+ 46°	Porter	1901
275°	+ 45°	Boss	1901
277° 30′	+ 20°	Campbell (from stellar spectroscopic measures)	1902
Velocity=12·4 miles per second (Campbell).			

2. Stellar Velocities.

Name of Star.	Rate.	Direction.	Remarks.
	Miles per Sec.		
δ Leporis	58	Receding	Campbell, 1901

η Cephei	54	Approaching	” 1899
θ Canis Majoris	60	Receding	” 1901
ι Pegasi	47	Approaching	” “
μ Sagittarii	47	Approaching	” “
ε Andromedæ	52	Approaching	” “
ζ Herculis	44	Approaching	Bélopolsky, 1893
61 Cygni	34	Approaching	” “
μ Cassiopeiæ	60	Approaching	Campbell, 1901
1830 Groombridge	59	Approaching	” “
Arcturus	4·3	Approaching	Keeler, 1890
Arcturus	278	Tangential	Accepting Elkin’s parallax of 0·024′
1830 Groombridge	150	Tangential	Parallax = 0·14′
μ Cassiopeiæ	113	Tangential	Parallax = 0·10′ (Peter)
Z. C. 5h 243	82	Tangential	Parallax = 0·312′ (Gill)
Lacaille, 2,957	78	Tangential	Parallax = 0·064′ (Gill)
Lacaille, 9,352	73	Tangential	Parallax = 0·283′ (Gill)
o2, Eridani	72	Tangential	Parallax = 0·166′ (Gill)
ε Eridani	61	Tangential	Parallax = 0·149′ (Gill)

TABLE V.

LIST OF GREAT TELESCOPES.

1. Reflectors—A. Metallic Specula.

Locality.	Aperture in Inches.	Focal Length in Feet.	Constructor.	Remarks.
Birr Castle, Parsonstown, Ireland	72	54	Third Earl of Rosse, 1845	Newtonian.
Melbourne Observatory	48	28	T. Grubb, 1870	Cassegrain.
Birr Castle	36	—	Third Earl of Rosse, 1839	Newtonian. Remounted equatoreally 1876.
Royal Observatory Greenwich	24	20	William Lassell, 1846	Newtonian. Presented by the Missess Lassell to the Royal Observatory
B. Silvered Glass Mirrors.				
Ealing, near London	60	27	A. A. Common, 1891	Newtonian.
Yerkes Observatory	60	25	G. W. Richey, 1902	Can be employed at choice as a Coudé or a Cassegrain.
National Observatory, Paris	48	—	Martin, 1875	Newtonian. Remodelled for spectrographic work by Deslandres in 1892
Meudon Observatory	39	9·7		
Lick Observatory	36	17·5	Calver, 1879	Mounted by Common at Ealing in 1879. Sold by him to Crossley, 1885. Presented by Crossley to the Lick Observatory, 1895.
Toulouse Observatory	32·5	16·2	Brothers Henry	
Marseilles Observatory	31·5	—	Foucault	
Royal Observatory, Greenwich	30	—		Cassegrain. Mounted as a counterpoise to the Thompson equatoreal.
Westgate-on-Sea	30	—	Common, 1889	The property of Sir Norman Lockyer.

Harvard College Observatory	28	—	H. Draper, 1870	Mounted for spectrographic work,1887.
Royal Observatory, Edinburgh	24	—	T. Grubb, 1872	
Daramona, Ireland	24	10·5	Sir H. Grubb, 1881	Remounted 1891. Owned by Mr. W. E.Wilson.
Yerkes Observatory	23·5	7·7	Ritchey, 1901	Ritchey, Cassegrain, with an equivalent focal length of 38 feet.
Harvard College Observatory	20	—	Common, 1890	
Crowborough, Sussex	20	8·2	Sir H. Grubb, 1885	Mounted with a 7-inch refractor.
2. Refractors.				
Palais de l'Optique, Paris	49·2	197	Gautier, 1900	Mounted as a siderostat in connection with a plane mirror 79 inches across.
Yerkes Observatory	40	62	Alvan G. Clark, 1897	
Lick Observatory	36	57·8	A. Clark and Sons, 1888	For photographic purposes a correcting lens is available, of 33 inches aperture, 47·8 feet focus.
Meudon Observatory	32·5	55·2	Henrys and Gautier, 1891	Mounted with a photographic refractor of 24·4 inches aperture.
Astrophysical Observatory, Potsdam	31·5	39·4	Steinheil and Repsold, 1899	Photographic. Mounted with a visual refractor 20 inches in aperture.
Bischoffsheim Observatory, Nice	30·3	52·6	Henrys and Gautier, 1886	Visual. Mounted on Mont Gros, 1,100 feet above sea level.
Imperial Observatory, Pulkowa	30	42	A. Clark and Sons, 1885	Visual. Mounted by Repshold.
National Observatory, Paris	28·9	—	Martin	
Royal Observatory, Greenwich	28	28	Sir H. Grubb, 1894	Visual and photographic. Mounted by Ransome and Simms.
University Observatory, Vienna	27	34	Sir H. Grubb, 1881	Visual.
Royal Observatory, Greenwich	26	26	Sir H. Grubb, 1897	The Thompson photographic equatoreal.
Naval Observatory, Washington	26	29	A. Clark and Sons, 1873	
Leander McCormick Observatory, Virginia	26	32·5	A. Clark and Sons, 1881	
Cambridge University Observatory	25	—	T. Cooke and Sons. 1870	Presented to the University in 1889 by Mr. R. S. Newall.
Meudon Observatory	24·4	52·2	Henrys and Gautier, 1891	Photographic. Mounted with a visual 32·5-inch refractor.
Harvard College Observatory	24	11·3	A. Clark and Sons, 1893	Photographic doublet. The gift of Miss Bruce. Transfered in 1896 to Arequipa, Peru.
Royal Observatory, Cape of Good Hope	24	22·6	Sir H. Grubb, 1898	Photographic. The gift of Mr. McClean. Mounted with an 18-inch visual refractor.
Lowell Observatory, Flagstaff, Arizona	24	31	Alvan G. Clark, 1896	Visual. First mounted near the city of Mexico. Installed at Flagstaff, 1897.
National Observatory, Paris	23·6	59	Henrys and Gautier, 1891	Visual and photographic. Mounted as an equatoreal Coudé.
Halsted Observatory, Princeton, N.J.	23	32	A. Clark and Sons, 1883	
City Observatory,	22	30	—	Mounted as a visual equatoreal on the Calton Hill,

Edinburgh				1898.
Etna Observatory	21·8	—	Merz, 1897	
Buckingham Observatory	21·2	—	Buckingham and Wragge	
Porro Observatory, Turin	20·5	—	Porro	
Chamberlin Observatory, Colorado	20	28	Alvan G. Clark and Saegmüller, 1894	Visual. Fitted with a reversible crown lens for photography.
Manila Observatory	20	—	Merz and Saegmüller, 1894	Visual. Provided with a photographic correcting lens.
Strasburg Observatory	19·2	23	Merz and Repsold, 1880	
Brera Observatory, Milan	19·1	23	Merz and Repsold	
Dearborn Observatory, Illinois	18·5	27	A. Clark and Sons, 1862	Mounted 1864
National Observatory, La Plata	18·1	29·5	Henrys and Gautier, 1890	Coudé Mount. Visual.
Lowell Observatory, Flagstaff, Arizona	18	26·3	Brashear, 1894	Mounted with a 12-inch Clark refractor as counterpoise.
Van der Zee Observatory, Buffalo, N.Y.	18	—	Fitz	Dismounted.
Bischoffsheim Observatory, Nice	16·5	26·2	Henrys and Gautier, 1889	Coudé Mount. Visual.
University Observatory, Vienna	16·5	29·5	Henrys and Gautier, 1890	Coudé Mount. Visual.
Jesuit Observatory, Zi-ka-Wei	16·5	22·5	Henrys and Gautier, 1897	Photographic. Mounted with a visual refractor of equal aperture.
Goodsell Observatory, Northfield, Minnesota	16·2	—	Brashear, 1891	
Warner Observatory, Rochester, N.Y.	16	22	A. Clark and Sons, 1891	
Grand-Ducal Observatory, Königsstuhl, Heidelberg	16	6·6	Brashear and Grubb, 1900	A twin photographic doublet. The gift of Miss Bruce. Mounted with a visual 10-inch refractor by Pauly.
Meudon Observatory	15·7	5·3		
Washburn Observatory, Wisconsin	15·6	20·3	A. Clark and Sons, 1879	
Teramo Observatory, Italy	15·5	—	T. Cooke and Sons, 1885	Formerly the property of Mr. Wigglesworth.
Royal Observatory, Edinburgh	15·1	—	T. Grubb, 1872	Presented by Lord Crawford.
Madrid Observatory	15	-	Merz	
Tulse Hill Observatory	15	15	Sir H. Grubb, 1870	Lent by the Royal Society to Sir William Huggins. Mounted with an 18-inch Cassegrain reflector.
National Observatory, Paris	15	29	Lerebours	
Harvard College Observatory	15	22	Merz, 1847	

National Observatory, Rio de Janeiro	15	—		
Tacubaya Observatory, Mexico	15	15	Sir H. Grubb, 1880	
Stonyhurst College Observatory	15	15	Sir H. Grubb, 1893	
Brera Observatory, Milan	15	—		
University of Mississippi	15	15	Sir H. Grubb, 1893	Visual. Mounted with a photographic 9-inch refractor.
Imperial Observatory, Pulkowa	15	22·5	Merz and Mahler, 1840	
Maidenhead Observatory	15	—	Sir H. Grubb, 1893	The property of Mr. Dunn. Mounted with a twin photographic refractor.
Odessa Observatory	14·9	—	Merz, 1881	
Bischoffsheim Observatory, Nice	14·9	23	Henrys and Gautier	
Brussels Observatory	14·9	20	Merz and Cooke, 1877	
Observatory of Bordeaux	14·9	22·4	Merz and Gautier, 1880	
Observatory of Lisbon	14·9	—	Merz and Mahler	

TABLE VI.

List of Observatories employed in the Construction of the Photographic Chart and Catalogue of the Heavens.

All are provided with 13-inch photographic, coupled with 11-inch visual refractors:

Name of Observatory.	Constructors of Instruments.	
	Optical Part.	Mechanical Part.
Paris	Henrys	Gautier
Algiers	,,	,,
Bordeaux	,,	,,
San Fernando (Spain)	,,	,,
Vatican	,,	,,
Cordoba	,,	,,
Montevideo	,,	,,
Perth, Western Australia	,,	,,
Helsingfors	,,	Repsold
Potsdam	Steinheil	,,
Catania	,,	Salmoiraghi
Greenwich	Sir H. Grubb	Sir H. Grubb
Oxford	,,	,,
The Cape	,,	,,
Melbourne	,,	,,
Sydney	,,	,,
Tacubaya (Mexico)	,,	,,

FOOTNOTES:

[1630] *Comptes Rendus*, t. xliv., p. 339.

[1631] A. A. Common, *Memoirs R. Astr. Soc.*, vol. i., p. 118.

[1632] Newcomb, *Pop. Astr.*, p. 137.

[1633] *Month. Not.*, vol. liv., p. 67.

[1634] Keeler, *Publ. Astr. Pac. Soc.*, vol. ii., p. 160.

[1635] H. Grubb, *Trans. Roy. Dub. Soc.*, vol. i. (new ser.), p. 2.

[1636] Hale, nevertheless (*Astroph. Jour.*, vol. v., p. 128), considers that refractors preserve their superiority of visual light-grasp over Newtonian reflectors up to an aperture of 52-1/2, while equalisation is reached for the photographic rays at 34 inches.

[1637] *Astroph. Jour.*, vol. v., p. 130.

[1638] *Phil. Trans.*, vol. cxlviii., p. 465.

[1639] *Optics*, p. 107 (2nd ed., 1719).

[1640] *Observatory*, vol. viii., p. 85.

[1641] Holden on Celestial Photography, *Overland Monthly*, Nov., 1886.

[1642] *Observatory*, vol. xv., p. 283.

[1643] Bailey, *Astroph. Jour.*, vol. x., p. 255.

[1644] *Harvard Circulars*, Nos. 2, 18, 24, 33;

[1645] Loewy, *Bull. Astr.*, t. i., p. 286; *Nature*, vol. xxix., p. 36.

[1646] *Nature*, vol. xxiv., p. 389.

[1647] *Ibid.*, vol. xxix., p. 470.

[1648] *Trans. R. Dublin Soc.*, vol. iii., p. 61.

[1649] *Observatory*, vol. vii., p. 167.

[1650] Loewy, *Bull. Astr.*, t. i., p. 265.

[1651] *Phil. Trans.*, vol. clxxi., p. 653.

[1652] Janssen, *L'Astronomie*, t. ii., p. 121.

[1653] Rev. A. L. Cortie, *Astr. and Astrophysics*, vol. xi., p. 400.

[1654] *Phil. Mag.*, vol. xiii., 1882, p. 469.

[1655] *Bull. Astr.*, t. iii., p. 331.

INDEX

THE END

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THE STARS

BY

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131	13	identifiying	identifying
140	40	terrestial	terrestrial
143	25	appearence	appearance
149	27	bloodvessel	blood vessel
152	12	Angström	Ångström
169	3	undimished	undiminished
171	42	sympton	symptom
172	18	familar	familiar
173	42	photograpic	photographic
182	37	by which i structure	by which its structure
199	37	Bredikhine	Brédikhine
220	26	stata	strata
246	30-31	of its orbit 24 hours 53 seconds.	of its orbit in 24 hours 53 seconds
260	13	garden at its seasons	garden as its seasons
284	21	throngh	through
284	13	oparator	operator
376	42	promptly recognised. in a	promptly recognised in a
377	footnote 3	applie	applied
395	42	the gaseous fields o	the gaseous fields of
423	35	relatiouship	relationship
434	footnote 2	Optice	Optics
436	42	Its resumption, ofter some years	Its resumption, after some years
436	footnote 1	(two references given, within a single footnote. In the text footnote 1 used twice)	(split into two footnotes, and corrected references in the text)
450	27	1862 Conclusion of a	1872 Conclusion of a
454	40	spectographically	spectrographically
454	18	spectographic	spectrographic
456	4	Lyrae	Lyræ
488	index	Wolf, R., sun-spot and magnetic periodicity, 128, 164, 162;	Wolf, R., sun-spot and magnetic periodicity, 128, 162, 163;