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ASTRONOMICAL PHYSICS

ASTRONOMICAL PHYSICS

BY

F. J. M. STRATTON

D.S.O., M.A., F.R.A.S., F.INST.P.

FELLOW AND LECTURER OF GONVILLE AND CAIUS COLLEGE, FORMERLY
ASSISTANT DIRECTOR OF THE SOLAR PHYSICS OBSERVATORY,
CAMBRIDGE UNIVERSITY

WITH THIRTY-TWO PLATES &c.



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PREFACE

THIS book was projected in days of comparative freedom for astronomical work before the break caused by the European War. It became subsequently the spare time occupation of a busy teacher. It contains doubtless sins of commission, but the writer is more conscious of the sins of omission caused by trying to compress a large and growing subject within a given space. His aim has been to provide a useful book on the subject for the student, and one which every astrophysicist and not a few spectroscopists would want constantly within reach. This he has attempted by giving full references, especially to modern investigations, and more particularly by including in the appendices a number of tables which at present have to be hunted up each in one of a dozen scattered volumes. Should a fresh edition of the book be required—and the rate at which new knowledge on its subject matter is pouring in justifies a hope of a later and revised edition—the writer would gladly add other tables which may be suggested by the experience and needs of other workers in the field.

It only remains for the writer to express his indebtedness to many colleagues and friends for kindly assistance. To Professor Newall, who has helped more often and more widely than he knew, the writer owes a

deep personal debt. In suggestion and friendly discussion his wide knowledge of the subject matter of the book has been freely accessible; he has further supplied several plates and offered facilities for preparing other plates, which have been of great help. Mr. Ba~~nd~~all has helped greatly with the chapter on "Stellar Classification," and has prepared Appendix VIII. Mr. Butler has prepared several plates and figures, and has been particularly helpful with the chapter on "The Sun." To the Council of the Royal Society, the Munich Academy of Science, the Editors of the *Astrophysical Journal*, the Astronomer Royal, the Directors of the Cambridge, Edinburgh, Lick, Lowell, Meudon, Norman Lockyer, Mount Wilson, Victoria and Yerkes Observatories, hearty thanks are due for kindly allowing the publication of many of the plates in the book, while members of their staffs have been exceedingly kind in preparing photographs or plates for publication. In particular the writer would wish to express his thanks to Monsieur Deslandres for his photographs, and to Dr. J. S. Plaskett and Mr. H. H. Plaskett for the care taken in selecting the material for Plates 23 and 24. To Mr. W. H. Manning the writer is especially indebted for the trouble taken in preparing the photographs for the publishers. Lastly, the writer wishes to thank Mr. E. A. Milne and Dr. W. M. Smart for reading the manuscript, for their timely corrections and helpful suggestions.

The standard notation adopted at the International Astronomical Union at Rome in 1922 has been used throughout.

CAMBRIDGE,

August, 1924.

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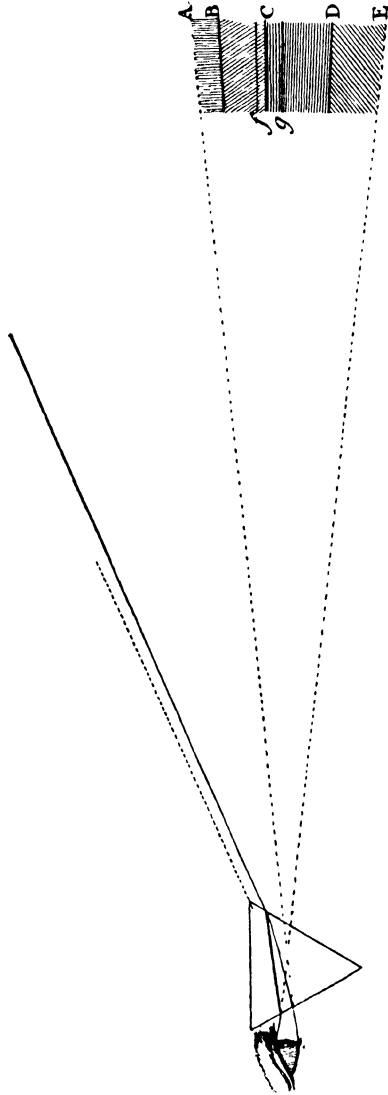
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LIST OF THE PRINCIPAL ABBREVIATIONS USED IN THE FOOTNOTES

Phil. Trans.	.	.	Philosophical Transactions of the Royal Society of London.
Proc. R. S.	.	.	Proceedings of the Royal Society of London.
M. N. R. A. S.	.	.	Monthly Notices of the Royal Astronomical Society of London.
Ap. J.	.	.	Astrophysical Journal.
A. J.	.	.	Astronomical Journal.
A. and Ap.	.	.	Astronomy and Astrophysics.
A. N.	.	.	Astronomische Nachrichten.
C. R.	.	.	Comptes Rendus de l'Académie des Sciences, Paris.
Potsdam Pub.	.	.	Publikationen des Astrophysikalischen Observatoriums zu Potsdam.
Harvard Annals	.	.	Annals of the Harvard College Observatory.
H.C.O. Cir. or Bull.	.	.	Circular or Bulletin of the Harvard College Observatory.
Pub. D. A. O.	.	.	Publications of the Dominion Astrophysical Observatory, Victoria, B.C.
Pub. A. S. P.	.	.	Publications of the Astronomical Society of the Pacific.
Phil. Mag.	.	.	Philosophical Magazine.
Proc. N. A. S.	.	.	Proceedings of the National Academy of Sciences, Washington.
Trans. I. A. U.	.	.	Transactions of the International Astronomical Union.
B. A. N.	.	.	Bulletin of the Astronomical Society of the Netherlands.
Pop. Ast.	.	.	Popular Astronomy.
Jour. B. A. A.	.	.	Journal of the British Astronomical Association.



WOLLASTON'S DIAGRAM OF THE DARK LINES IN THE SUN'S SPECTRUM

ASTRONOMICAL PHYSICS

CHAPTER I

MAINLY HISTORICAL

1. Early Observations.—In the history of the forward movement of any science there can be traced a series of investigations, which to the later student stand out as guide-posts, leading from areas of entrenched knowledge through what had long been “no man’s land” into newly-won territory. It is difficult to say for astrophysics exactly where the series of guide-posts begins, but, if we take time to be an important factor in deciding the starting-point, we can ignore Newton’s discovery in 1675 of the composite nature of white light and commence with Wollaston’s discovery in 1802 * of the dark lines in the solar spectrum. On viewing through a prism of flint glass, a beam of daylight admitted to a darkened room by a crevice one-twentieth of an inch broad, Wollaston noted (Plate 1) that the beam was separated by dark lines into four colours—red, yellowish-green, blue, and violet—and concluded that he had found the elementary colours that make up white light. Wollaston further noticed that if the blue light from the lower part of a candle flame was examined similarly through a narrow slit and a prism a series of bright images were formed, one of which corresponded with the division between blue and violet in the solar spectrum.

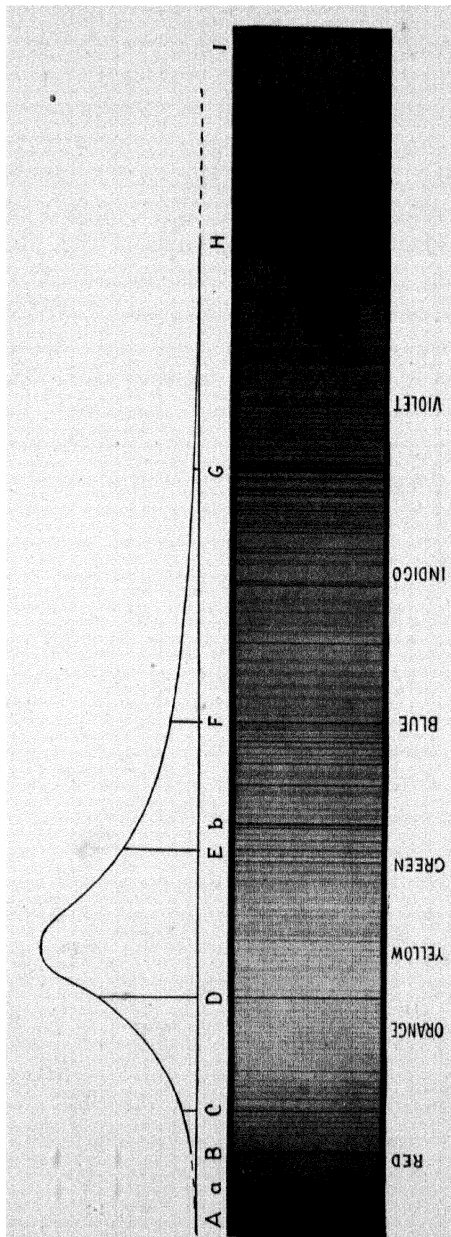
* *Phil. Trans.*, xcii. 378, 1802.

The suggestion underlying this coincidence was not to be developed for many years. Meanwhile a much more accurate and detailed examination of the dark or absorption lines of the solar spectrum was made in 1814 by Fraunhofer.* Using a narrower slit, a telescope to view the spectrum and a more elaborate method of plotting the positions of the lines, he increased Wollaston's seven lines in the solar spectrum to 574; further, he slightly widened the range of spectrum examined, and he mapped out all the lines observed. Some of the stronger lines or groups he identified by letters—A, a, B, C, D, E, b, F, G, H, which have remained in general use to the present day.† (Plate 2.)

Among many fresh points brought out by Fraunhofer may be mentioned the following. The focus of the telescope through which the spectrum was observed had to be altered in order that an observer might see clearly the lines in the different parts of the spectrum. Reflected sunlight from Venus showed the strongest lines seen in the solar spectrum [D, E, b, F], while the light of Sirius gave three strong lines not resembling anything found in the solar spectrum. In fact, the stars differed from each other as well as from the sun in the prismatic analysis of their light. Light from various terrestrial sources also differed in the character of the bright or emission lines produced. Fraunhofer noted the coincidence of the dark [D] lines of the solar spectrum with a pair of bright lines observed in the light from the flame of a lamp and their resemblance in strength and the equality in separation. Thirty-five years elapsed before this observation was repeated, and then it

* *Denkschriften der Königlichen Acad. d. Wiss. zu München*, v. 202, 1814.

† The International Astronomical Union, Rome, 1922, adopted a recommendation to enclose these letters in square brackets when used for lines in the spectrum in order to avoid confusion with other notations.



FRAUNHOFER'S MAP OF THE SOLAR SPECTRUM

was done in a manner which, for the first time, threw light on the significance of the coincidence.

Foucault, speaking at the Société Philomathique de Paris in 1849,* reported that, having noticed two lines in the spectrum of the carbon arc which resembled the [D] lines in the solar spectrum, he had by means of a convergent lens projected a solar image on to the arc and had observed the two spectra superposed. The bright double line of the arc coincided exactly with the dark double line of the solar spectrum. Further, the arc absorbed the lines [D] of the solar light, which appeared darker than usual when viewed through the arc, and, when a bright point which gave a continuous spectrum was viewed through the arc, the [D] lines appeared dark as in the solar spectrum. Thus, the arc offered us a medium which emitted the [D] lines on its own account and at the same time absorbed them when they came from elsewhere. The [D] lines only appeared weakly when the arc was struck between iron or copper poles, but could at once be enormously strengthened if the poles were touched with potassium or sodium. The source of the [D] lines was not fully determined, but "the phenomenon seemed to constitute a pressing invitation to study the spectra of the stars, for if this same ray was found there, stellar astronomy would obtain useful results from it." The invitation was, however, not to be accepted for some years, and it was not until 1859 that the next, and perhaps the most fundamental, step towards the new science was taken by Kirchhoff at Heidelberg.

2. The Origin of Dark Spectral Lines.—In the course of an examination of the spectra of coloured flames by Bunsen and Kirchhoff,† the following observations were made. A solar spectrum was formed by projection and the rays,

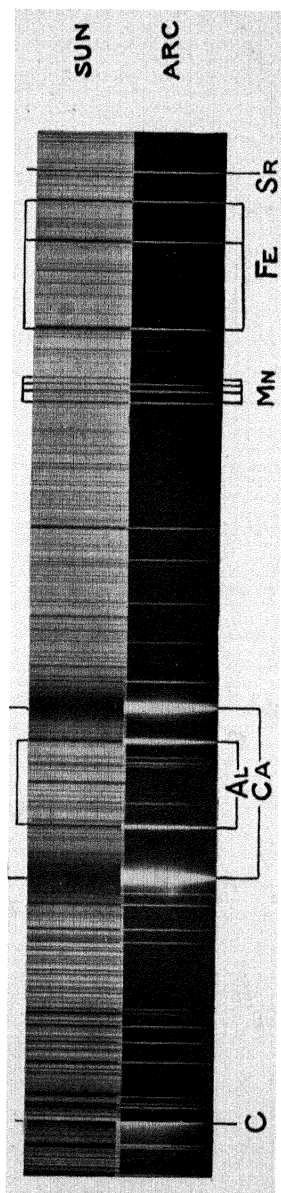
* *L'Institut*, xvii. 45, 1849.

† *Monatsberichte d. K. Preuss. Akad. d. Wiss. zu Berlin*, 1859, 662.

before they fell on the slit, were passed through a powerful salt-flame. "If the sunlight were sufficiently reduced, there appeared in the place of the two dark lines D two bright lines; if, on the other hand, its intensity surpassed a certain limit, the two dark lines D showed themselves in much greater distinctness than without the employment of the salt-flame. . . . I conclude," said Kirchhoff, "from these (and other) observations that coloured flames, in the spectra of which bright sharp lines present themselves, so weaken rays of the colour of these lines, when such rays pass through the flames, that in place of the bright lines dark ones appear as soon as there is brought behind the flame a source of light of sufficient intensity. . . . I conclude further that the dark lines of the solar spectrum, which are not evoked by the atmosphere of the earth, exist in consequence of the presence in the incandescent atmosphere of the sun, of those substances which, in the spectrum of a flame, produce bright lines at the same place. We may assume that the bright lines agreeing with D in the spectrum of a flame always arise from sodium contained in it; the dark line D in the solar spectrum allows us, therefore, to conclude that there exists sodium in the sun's atmosphere."

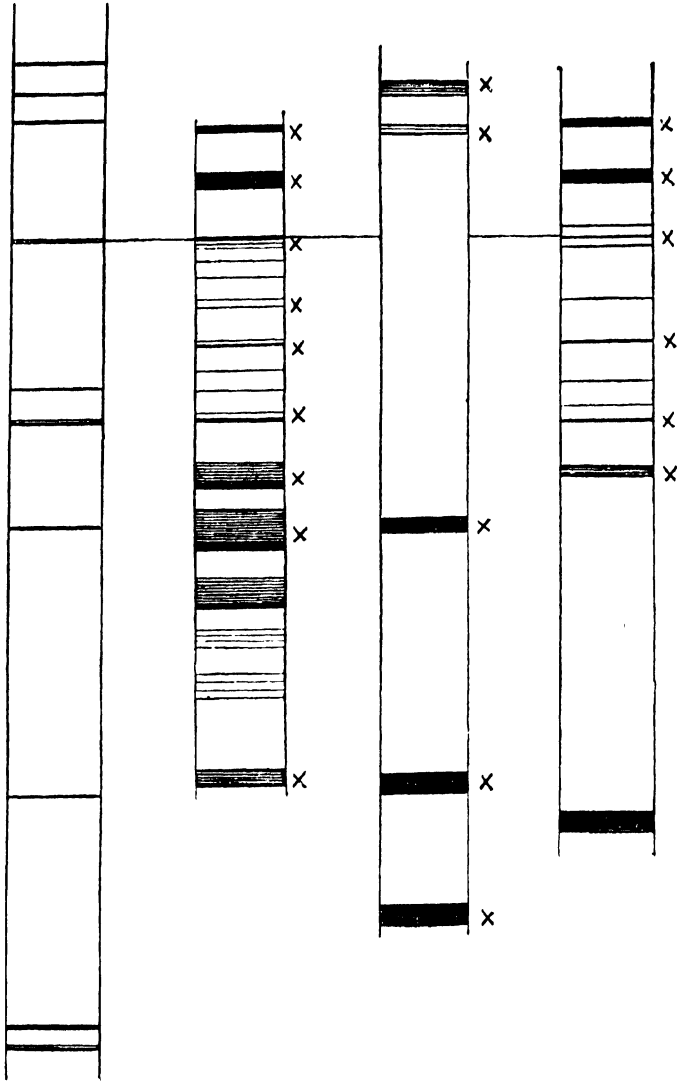
This explanation of the origin of Fraunhofer's lines authorized conclusions respecting the material constitution of the atmosphere of the sun (Plate 3), and suggested to Kirchhoff an application to the brighter fixed stars. Luckily this time, the challenge was not allowed to pass unnoticed. It came at a time when a vague longing after newer methods of observation for attacking many of the problems of the heavenly bodies was occupying the mind of a young amateur astronomer, by name William Huggins. The news of Kirchhoff's discovery was to him, he said,* "like the coming upon a spring of water in a dry and thirsty land. A feeling as of inspiration seized me. I felt as if I had it now in my

* *The Nineteenth Century Review*, June, 1897.



COMPARISON OF SOLAR AND ELECTRIC ARC SPECTRA OF CALCIUM, STRONTIUM, IRON, MANGANESE, ALUMINIUM, CARBON, ETC., SHOWING PRESENCE OF THESE ELEMENTS IN SOLAR ATMOSPHERE

Photographed by C. P. Butler with 21 ft. Rowland Concave Grating at Solar Physics Observatory, London, 1897



HUGGINS'S EARLY DRAWINGS OF STELLAR SPECTRA

power to lift a veil which had never before been lifted ; as if a key had been put into my hands which would unlock a door which had been regarded as for ever closed to man—the veil and door behind which lay the unknown mystery of the true nature of the heavenly bodies.”

3. Early Stellar Researches.—Huggins secured the assistance of Professor W. A. Miller, of King’s College, London, in his attack on the very difficult problem of extending Kirchhoff’s discovery to the stars. With great ingenuity and persistence they overcame the many serious instrumental difficulties. Simultaneously with Secchi in Rome, and a month after Rutherford in America, Huggins and Miller published, in February, 1863, a preliminary note on stellar spectra * (Plate 4) ; they were easily first in the field in the careful analysis of stellar spectra which the Royal Society published in the following year.† The spectra of the brighter stars were examined simultaneously with the spectra of ten to twenty elements and identifications of lines were made with considerable certainty. In part, at least, the riddle of the Universe had been solved. The stars, though differing from one another in the kinds of matter of which they consisted, were found to be all constructed on the same plan as the sun and composed of matter identical, at least in part, with the materials of our system. A common chemistry was now known to exist throughout the visible universe.

A general unity having been established, the next step was to examine the underlying diversity of type and this was first done in detail by Secchi, in 1866.‡ He observed some 300 stars which he fitted into a framework of four main types. The question of stellar classification will be discussed in detail in a later chapter. It is mentioned here as it has been a fundamental factor in the development of the science of stellar spectroscopy.

* *Proc. R.S.*, xii. 444, 1863. † *Phil. Trans.*, cliv. 413, 1864.

‡ *C.R.*, lxiii. 621, 1866 ; *A.N.*, lxxiii. 129, 1868.

4. Introduction of Photography.—The extension to spectroscopic work, which was made possible by the introduction of photography, and the enormous increase in accuracy resulting therefrom, entitle it to be included amongst the early sign-posts which pointed out the line of development of the new science of stellar physics. The first photographic spectrum of the sun which was published, was obtained in December, 1872, by Dr. Henry Draper.* The earliest recorded attempt at the photography of stellar spectra was made by Huggins and Miller in 1863; but, owing to instrumental difficulties, the plate secured presented no indication of lines. It was not until 1876 that Huggins secured a photograph of a stellar spectrum showing the stronger lines of the spectrum.† Meanwhile, Dr. Henry Draper, in New York, had also obtained, in 1872, photographs of the spectra of several stars.‡ Huggins soon saw the value of replacing the wet plate by the dry plate. Results of importance immediately followed, notably an increase in the accuracy of measurement of stellar lines and the extension of the series of hydrogen lines towards the ultra-violet. In the hands of Balmer and Rydberg this laid the foundation of the study of series in spectra. Many new developments at once became possible, and the science began to branch out along many different lines. Important discoveries and advances were still to be made, but these will be best described in the separate chapters to which they more appropriately belong. Meanwhile, it is necessary to make reference to the instruments used in astrophysical researches and to allied laboratory investigations, so that the account of the later researches may be given without frequent explanatory interruptions.

* *American Journal of Science*, vi. 401, 1873.

† *Proc. R.S.*, xxv. 445, 1876.

‡ *American Journal of Science* (3), xiii, 95, 1877, and xviii, 419, 1879.

CHAPTER II
INSTRUMENTS

5. The Stellar Spectroscope. (*a*) *The Objective Prism and Prismatic Camera.*—The first instrument used to examine a star's spectrum consisted of a prism placed in front of the object-glass of a telescope; the prism was large enough for the refracted beam of star-light to fill the object-glass of the telescope. A composite beam of parallel rays from the star strikes the outer surface of the prism; corresponding to each element in colour of the incident beam a group of refracted rays emerges from the prism as a parallel beam, the direction of the refracted beam depending on the wavelength or colour of the element concerned. This beam gives a point image of the star after passing through the objective of the telescope. Adding the effects of the separate elements we get for the star's image not a point but a narrow line, of width equal to the diameter of the star's image, and ranging in colour from red at one end to violet at the other. Corresponding to the absorption lines in the star's spectrum there are gaps in the narrow line-image, but these are very difficult to see; Fraunhofer, who used this instrument, adopted the device of a cylindrical lens to widen the narrow line-image at right angles to its length so as to form a band. This cylindrical lens was placed between the prism and the object-glass of the telescope with its axis at right angles to the edge of the prism. The length of the coloured line-image was not changed, but it was widened parallel to itself into a band, and the gaps in the line-image were

changed into dark lines running across the band. In the modern form of the objective prism spectrograph, the prismatic camera, as used at Harvard in the formation of the Draper Catalogue of Stellar Spectra, the eye-piece for observing the spectrum is replaced by a photographic plate, the spectra of a whole field of stars being secured at the same exposure. Instead of using a cylindrical lens to widen the spectra of the stars, the images of the stars are allowed to trail slowly across the plate in a direction parallel to the edge of the prism and to the extent necessary to secure measurable spectra. The prism in front of the object-glass in this instrument is called an objective-prism.

(b) *The Direct-Vision Spectroscope*.—By the use of five prisms, three of crown glass, and two of flint glass arranged

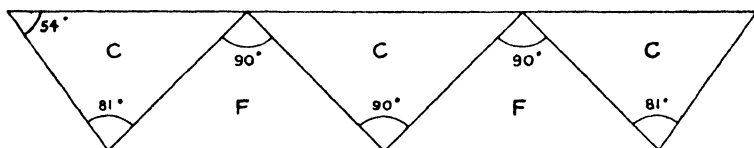
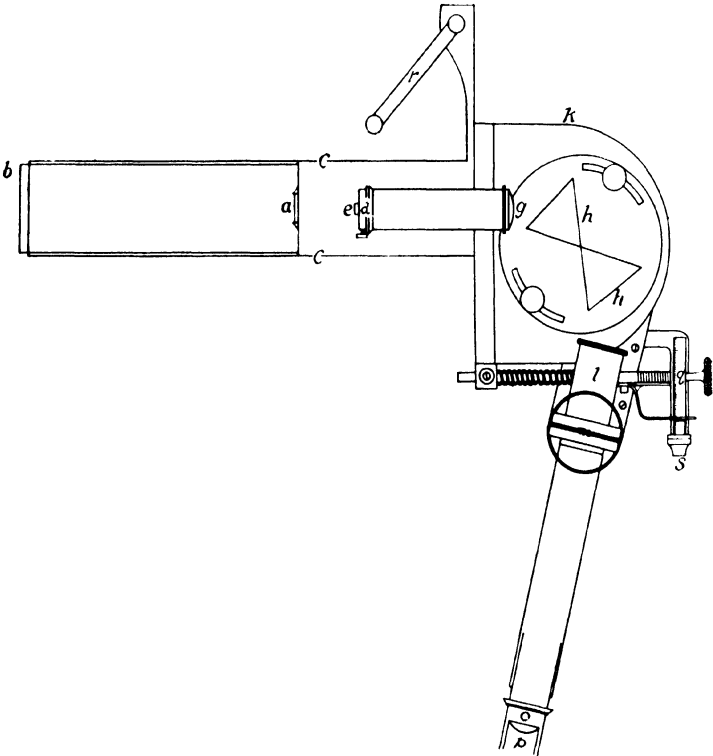


FIG. 1.

as in the figure, Janssen designed a spectroscope which gave no deviation for a ray of a given wave-length, though rays of shorter or greater wave-length were bent and a spectrum was formed.

Thus the tube in which the prisms were mounted could be pointed at a bright line, and if held at the proper angle, the source of light was seen spread out into a coloured band. Secchi used this type of instrument for his earlier work. It is a handy instrument of use mainly for qualitative examination of stellar or laboratory spectra. It is not an effective type for exact work on stellar spectra, but it can be employed with advantage on very faint spectra when the time involved prohibits the use of photography.

(c) *The Prismatic Slit-Spectroscope*.—The great draw-



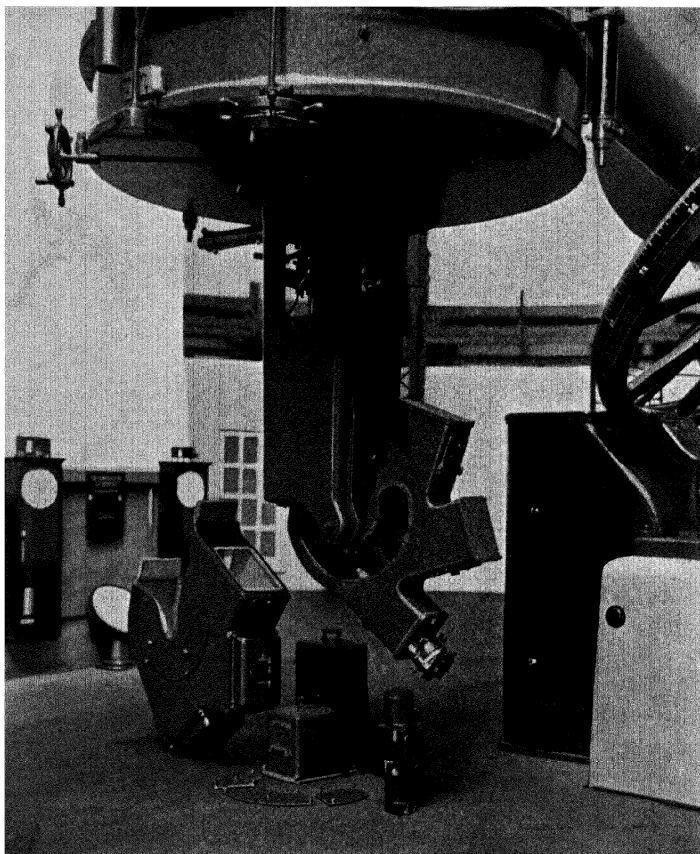
HUGGINS'S FIRST STELLAR SPECTROSCOPE

back of the prismatic camera for stellar work is that it does not admit of any easy and reliable method of comparing the stellar spectrum with that of some known terrestrial source. This is important, not merely for identification purposes, but also for all investigations dependent on the exact position in the stellar spectrum (i.e. the observed wave-length) of lines of known chemical origin. Huggins saw from the start the need for the comparison of stellar with terrestrial spectra, and in its essentials the slit-spectrograph of to-day reproduces the features of his first instrument (Plate 5). We will describe this first. The image of the star was formed by the object-glass of the telescope and thrown upon a narrow slit. The beam of rays converging from the object-glass to the slit was caught by a cylindrical lens placed a little way in front of the slit with its axis at right angles to the slit, so that the point image of the star was broadened slightly along the slit. A collimating lens was placed between the slit and the prisms with a principal focus at the slit so that the beam of light from the star image emerged as a bundle of parallel beams on to the prisms. Two 60° prisms of flint glass with their edges perpendicular to the refracted beams were used to disperse the beams and the resulting spectrum was viewed through a small achromatic telescope. In front of the slit and over half of it was placed a right-angled prism which reflected an image from some terrestrial source of light on to the slit. The star's spectrum and the terrestrial spectrum were viewed simultaneously and coincidences of lines in the two spectra could be observed. The methods adopted for measuring the positions of lines need not be discussed, as for all exact work photographic plates have replaced the earlier visual observations. The development of photographic methods led to several modifications of the apparatus amongst which the following may be mentioned. The eye-piece of the spectroscope was replaced by the camera lens and photographic

plate of the spectrograph. The cylindrical lens was abolished, the star being allowed to drift along the slit between two defined marks. This was easily done by setting the slit in the direction of the daily motion, and making the clock run a little slow. By the use of a slow motion control in right ascension the star could be made to trail across the proper portion of the slit as often as necessary. In order to observe the slit and the star's image on it for the purposes of accurate guiding, the jaws of the slit were made of polished speculum metal. The slit was illuminated by a feeble red lamp. The image of the star being wider than the slit, it was possible to view both through an eye-piece and to check the position of the stellar-image on the slit. By slightly tilting the slit-jaws it was possible to arrange that this eye-piece should be outside the beam of rays converging from the object-glass of the telescope to form the image of the star on the slit.

The comparison spectrum was generally obtained from an electric arc or spark between metallic electrodes; an image of the arc or spark was thrown on the slit on each side of the portion of the slit over which the star had trailed—care being taken first to cover by a screen the portion reserved for the star. At first the comparison spectrum was photographed at the beginning and end of the stellar exposure. As a later refinement the comparison spectrum was obtained from a series of short exposures made at regular intervals during a long stellar exposure. The exposure on the star had to be interrupted while the comparison spectrum was being photographed, care being taken that no light from the arc or spark fell on the part of the slit or plate reserved for the star image and spectrum respectively. In the latest designs the comparison spectrum can be added at any time without interfering with the stellar work and without affecting the spectrum of the star.

The growing exactitude of photographic work and the



STELLAR SPECTROGRAPH OF THE 72-INCH REFLECTING TELESCOPE AT
THE DOMINION ASTROPHYSICAL OBSERVATORY, VICTORIA, B.C.

increased requirements of the later researches have led to a further important modification of the simple stellar spectrograph designed by Huggins. For all work of high accuracy the spectrograph has to be kept at as constant a temperature as possible, and various jackets, warmed by electric currents have been designed to meet this need. It is not within the scope of this book to enter in detail into the designs of spectrographs to meet the requirements of special lines of work. For each problem there will be one design which will be the most suitable; the design is, however, severely conditioned by the amount of light available, and this, again, depends on the size of the telescope for which the spectrograph is designed and the faintness of the stars which it is intended to study. Considerations which have guided astronomers in the past in the designs of their spectrographs have been fully stated elsewhere, and references are given in a footnote.* (Plate 6.)

6. The Grating Spectroscope.—So far we have only been considering spectra formed by the passage of light through glass prisms. Newton, Wollaston, Fraunhofer all obtained their results in this way. But in 1821 another method was devised by the last-named by which the light from an illuminated slit could be dispersed to form a spectrum or rather a series of spectra.† When a monochromatic pencil of rays of light from a slit passes through a collimating lens

* Tulse Hill, *A. and Ap.*, xii. 117, 1893, and *Ap. J.*, i. 359, 1895; Lick, *Ap. J.*, viii. 123, 1898; xi. 259, 1900; and xii. 274, 1900; Yerkes, *Ap. J.*, xv. 1, 1902; Cambridge, *M.N.R.A.S.*, lxxv. 608, 636, 1905; Potsdam, *Ap. J.*, xi. 393, 1900; Lowell, *Ap. J.*, xx. 1, 1904; Mt. Wilson, *Ap. J.*, xxxv. 163, 1912; Victoria, *Ap. J.*, xlix. 209, 1919; Allegheny, *Publications of the Allegheny Observatory*, Vol. II, No. 1, 1912. See also *Ap. J.*, 1895, for papers by Michelson, Wadsworth and Keeler. For a non-mathematical discussion of the power of a spectroscope, see "The Spectroscope and its Work," by Newall. For a fuller account of the spectroscope, see "Spectroscopy," by Baly.

† *Denkschriften d. K. Akad. d. Wiss. zu München*, viiii. 1821.

so as to give a parallel beam of light, and strikes a grating consisting of a number of evenly-spaced narrow straight and equal apertures parallel to the slit, a bright image of the slit is formed flanked by narrow fainter images symmetrically placed on either side. If the light is composite, as sunlight is, corresponding to each of these images, a spectrum is formed. The observed facts have been explained in terms of the wave-theory of light according to which light is propagated by a series of waves or tremors in the ether. For each element of the spectrum there is a value for the wave-length (i.e. the interval between the successive crests of the waves) of the corresponding disturbance in the ether. The theory gives a connection between the wave-length of the light, the distance between successive apertures of the grating and the observed angle through which the light giving a particular line of the spectrum is deviated by the grating. Fraunhofer used the method to determine the wave-length of the [D] line for which he first obtained the value 588·8 millionths of a millimetre—correct to 1 part in 700*. The advantage of the grating over the prism for mapping purposes was obvious. For one thing it gave to each line a corresponding number which had a simple physical meaning independent of the details of the instrument used. Secondly, unlike the prismatic spectrum, the grating spectrum under certain conditions is *normal* or of constant scale per wave-length over a fairly large range, so that once the scale has been accurately determined and a fixed point identified, wave-lengths of lines may be read off at once by comparison with an accurate scale. This does not apply to the original plane grating designed by Fraunhofer, but to the concave grating designed by Rowland in 1882 and mounted and used in the way described below. We may note here that Ångström produced in 1868 the

* *Denkschriften d. K. Akad. d. Wiss. zu München*, viii. 1821, pp. 28-34; 1 millionth of a millimetre = 1 millimicron = 10^{-7} cm., and is generally written $\mu\mu$.

first normal map of the Fraunhofer lines in the solar spectrum giving the positions of some 1200 lines, of which 800 were identified with lines of common elements, notably iron, titanium, and calcium.* The unit he used, a tenth-metre or 10^{-10} metre, is still generally called an Ångström Unit, and its use is denoted by placing A after the number expressing the wave-length of a line. His map covered the range of wave-lengths from 3933A to 7320A. Rowland, who had modified the grating by ruling it on a *spherical mirror*, enlarged Ångström's Tables to about 20,000 lines between wave-lengths 2975A and 7331A and gave his results with much increased accuracy.† Rowland's wave-lengths are only now being gradually replaced by the International wave-lengths, of which details will be given later in this chapter. Some of the advantages of the grating over the prismatic spectrograph have been indicated. The chief disadvantage lies in the faintness of the spectral images formed. This has practically limited the grating spectroscope to laboratory and solar work, where it has been used most extensively.‡

The conditions of mounting referred to above which are necessary for securing a normal spectrum are as follows: The source of light must lie on the circumference of the circle, tangent to the grating and normal to the lines of the grating at its point of contact, which has as diameter the radius of curvature of the grating. The spectra are formed on the circumference of this circle and the *normal* spectrum is the one formed on the diameter of the circle through the point of contact. In the mounting adopted by Rowland the grating G and the photographic plate P (bent to the

* "Spectre normal du Soleil," Upsala, 1868.

† "Preliminary Table of Solar Wave-lengths," *Ap. J.*, i.-v. See, in particular, *ibid.*, i. 29, 1895.

‡ For a description of the 30-foot grating spectrograph used at Mt. Wilson Observatory, see *ibid.*, xxvii. 207, 1908.

curve of the circumference of the circle) move on two girders AB, AC, rigidly fastened at right angles to one another; GP is normal to the grating and of fixed length equal to the radius of curvature of the grating, so that P is the centre of curvature of the grating. A source of light at A gives a normal spectrum at P; A, G, P, all lie on the circle on GP as diameter.

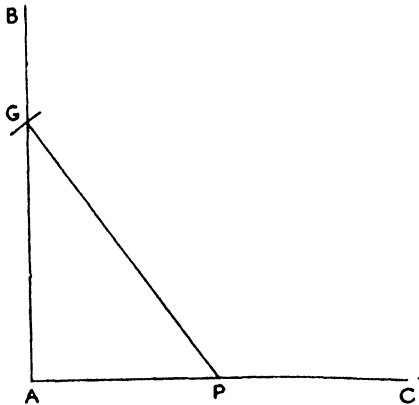


FIG. 2.

7. The Spectroheliograph.—In 1889 G. E. Hale, afterwards the first director of the Mount Wilson Observatory, designed a modification of the spectrograph which has proved of immense value in advancing the study of the solar atmosphere. The spectroheliograph enables a photograph of the sun's entire disc or of the prominences at its limb to be secured in terms of the light of a given wave-length. The principle of the instrument is briefly this. The image of the sun is formed as usual on a screen containing a narrow slit. The light from this slit passes through a train of prisms and mirrors and forms a spectrum in a plane parallel to that in which the solar image lies. A selected line in the spectrum is chosen and made to coincide with a second slit and the

photographic plate is placed close behind the second slit. Then the whole instrument except the photographic plate is made to move uniformly, at a rate which can be controlled, parallel to the planes containing the two slits or at right angles to the beams of light. Thus the first slit passes across the image of the solar disc and the photograph of successive elements of the sun's image in light of a given wave-length is built up on the photographic plate as the second slit moves across it. There are, as may well be expected, many niceties of adjustment and design required for a successful instrument of this nature, but they have all been most successfully met by its inventor and his colleagues.*

Various modifications of the above design have been tried by different investigators, the chief points of variation lying in the shapes of the slits, the movements of different portions of the apparatus—including the telescope and mirrors which feed the spectroheliograph—and the details of the optical train. One point might be briefly mentioned. The image of a long slit through a spectroscopie is a curved line. The use of a straight slit would give a distorted image of the sun. By curving the first slit so that its image is a curved slit of identical shape the difficulty of distortion has been overcome. One closely allied instrument that must be mentioned is the "*enregistreur des vitesses*" or velocity recorder of Deslandres. In this case instead of the motion of solar image and of photographic plate relative to the two slits being as continuous as possible, it is made up of a series of small discrete movements.† The photograph is built up of a series of strips, each of which contains a dark line. This line is part of an ordinary spectral picture of a

* See for the first account *A. and Ap.*, xii. 241, 1893, and for a later design of instrument, *Ap. J.*, xxiii. 54, 1906.

† See *Meudon Annales*, iv. 19, 1910, and *M.N.R.A.S.*, lxxiii. 327, 1913.

strip of the sun, the second slit of the instrument being broad enough to allow the whole width of the line to be seen and also any distortion of the line due to velocity in the line of sight of the vapours responsible for the line. (See Plate 13 and Chapter VII below.) The amount of the displacement from its normal position of the line at any point of the disc and consequently the motion of the corresponding gases can be determined by measuring the distance of the line from an accompanying fiducial line. Thus, the picture of the sun's disc in the light of a particular wave-length may be supplemented by a picture showing the behaviour of a given spectral line at all points of the disc.

8. Measuring Machines and Reductions.—When a stellar or solar spectrum accompanied in general by a known terrestrial comparison spectrum has been secured by one of the instruments described above its full value can only be obtained when it has been measured and the wave-lengths of the stellar or solar lines have been determined. The measurements can be made directly, the positions of both stellar and comparison lines being found on the standard scale of a comparator or measuring machine. One systematic error in measurement that has always to be taken into account is physiological in origin. Lines are measured too much to the right (or left) by an amount differing with their breadth and strength. This error is corrected, at any rate for symmetrical lines, by measuring the plate in two positions—red end of the spectrum to the right and then to the left. A residual error may remain in the measure of close blended or other non-symmetrical lines. The screw-errors or scale-errors of the measuring instrument have to be determined with care and the curved shape of the slit image may have to be taken into account. When the positions of the stellar lines are known relative to the comparison lines of known wave-length, the calculation of the wave-lengths of the stellar lines is fairly easy.

If the spectrum is a normal one derived from a grating, a simple interpolation gives the correct answer, but if the spectrum is prismatic, the dispersion differs along the spectrum and the reduction becomes slightly more complicated. If n is the measured scale value of a given line and λ is its wave-length, then for small ranges of the spectrum the Hartmann-Cornu * formula—

$$\lambda = \lambda_0 + \frac{c}{n - n_0},$$

is sufficiently exact for most purposes. The constants λ_0 , c , n_0 for any plate may be determined from three lines of the comparison spectrum taken near the extremes and the centre of the range concerned. The calculation involved is set out diagrammatically in Appendix II.

If a wider range is required, the same formula can be used, but an empirical correction can be added as follows: A number of comparison lines, in addition to the three used in determining the constants of the reduction, are measured, and the reduced wave-lengths of these lines are compared with the known values. Plotting the residuals against the wave-lengths, we may draw a freehand curve through the points and derive corrections to the reduced wave-lengths for any point in the range. Extrapolation outside the extreme standard lines is dangerous, and should be avoided when possible.†

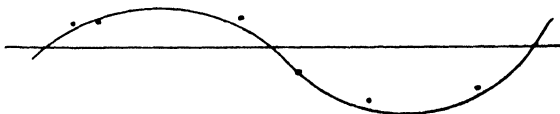


FIG. 3.

* "Potsdam Pub.," xii., Appendix, p. 5, 1902.

† For a modification of the simple Hartmann-Cornu formula, which admits of the use of more than three standard lines, see a paper by the author, *M.N.R.A.S.*, lxxi. 663, 1911.

A marked simplification in the calculations required in certain classes of work is obtained by the use of Hartmann's Spectrocomparator.* Where the spectrum to be measured is sufficiently like some standard spectrum, e.g. the solar spectrum, the star spectrum and the standard spectrum are both photographed with the same spectrograph and alongside the same comparison spectrum. By an arrangement of reflecting prisms and masks the two spectrograms are brought into the same field of view, alongside each other, care being taken to secure images of the same size. Corresponding lines in the standard and stellar spectra are made to coincide in position and then the amount by which one spectrogram has to be displaced to secure coincidence of neighbouring comparison lines is measured. From this we can deduce the difference of wave-length between the stellar line and the corresponding line in the standard spectrum.

9. Standard Scales of Wave-Lengths.—The first table of wave-lengths on a large scale was that of Ångström (referred to in § 6), which appeared in 1868. This was found to be in error owing to a wrong determination of the length of the standard metre at Upsala. Thalén corrected the measures and extended the work.† Müller and Kempf at Potsdam and Vogel measured over 4000 lines and established the Potsdam system of wave-lengths.‡ Meanwhile Rowland, working with higher dispersion and more powerful apparatus than the Potsdam investigators had been using, was preparing tables of wave-lengths on a much more elaborate scale, and during the years 1895-97 he published his "Preliminary Table of Solar Wave-Lengths." § There are

* *Ap. J.*, xxiv. 285, 1906.

† *Nova Acta Societatis Upsaliensis*, 3rd series, xii. 1884.

‡ *Potsdam Pub.*, v. 1886.

§ *Ap. J.*, i.-v. 1895-97. For corrections from Rowland's wave-lengths to the International system, see below, Appendix III (a).

certain systematic errors in this table due to the use of a grating and to variations in the physical conditions under which the spectra were secured, but the table was a splendid piece of work, and is even now only gradually being replaced in astronomical work by later and more accurate data.*

The International Solar Union decided, in 1905, that a new international standard should be formed. This was based, not on the [D] line, but on the red line of cadmium. This line might be said to define the International Ångström or (I.A.) unit. In an electric arc of 6 to 10 amperes, under a pressure of 760 mm. of mercury ($g = 980.67$) in dry air at 15° C., this line has, on the I.A. scale, a wave-length of 6438.4696 I.A. units. This value was adopted in 1907 by the International Solar Union. (Rowland's Table had been founded on the [D] line of sodium at 5896.155×10^{-10} m.) By means of intermediate standard lines in the green Fabry and Buisson, also Pfund and Eversheim, subsequently measured 86 iron arc lines by interferometer methods: the means of their three measurements were adopted by the Solar Union as secondary standards.† A list of these lines is given below in Appendix IV. A list of tertiary standards measured by several observers working with concave gratings was given by Kayser at the International Solar Union at Bonn in 1913, and is reproduced below in Appendix V. The International Astronomical Union meeting at Brussels in 1919 appointed a Committee to continue the work commenced by the earlier body. The International Solar Union at Bonn had laid down the conditions of the arc to be used for work on the tertiary

* For an account of the relations connecting this table to Rowland's earlier tables and to Prof. Kayser's "Normale Aus dem Bogen-spectrum des Eisens," 1900, see Hartmann, *Ap. J.*, xviii. 167, 1903.

† *Ibid.*, xxxii. 215, 1909; xxxiii. 85, 1910; xxxix. 94, 1913.

standards.* Already, however, St. John has shown † that the international arc gives lines displaced by the pole effect, i.e. the wave-lengths are affected by disturbing conditions in the arc that are associated primarily with proximity to the poles of the arc. St. John suggested as preferable to the arc agreed upon at Bonn, a Pfund arc ‡ 12 mm. long, carrying 5 amperes or less, operated between 110 and 250 volts, used over a central zone at right angles to the axis of the arc not more than 1.25 mm. in width, and with an iron rod 7 mm. in diameter, as the upper electrode. He added that the wave-lengths already published are not sufficiently free from pole-effect to comply with the more and more exacting demands that will be made upon such fundamental data.

In the report of a committee on wave-lengths of lines to the International Astronomical Union at Rome, 1922, St. John gave a further list of secondary and tertiary standard iron lines which had been measured by himself and other workers. These fresh lines have been adopted, and have been incorporated below, in Appendices IV and V. St. John also suggested a number of lines of neon and a number of iron lines outside the range of previous tables as suitable for new standards and indicated which of the old standards ought now to be abandoned.

10 (a). Photometers.—As one of the important developments of stellar physics is closely identified with stellar magnitudes, a brief description of the more important instruments in use in stellar photometry must be given. The wedge photometer was first invented by Pritchard, of Oxford.§ It consists essentially of a wedge of neutral-tinted glass cemented to a similar wedge of clear glass and made to slide close to the eye-piece of a telescope. The scale of the wedge can be determined in the laboratory and

* *Observatory*, xxxvi. 358, 1913.

† *Ap. J.*, xxvii. 297, 1907.

‡ *Ap. J.*, xlvi. 165, 1917.

§ *M.N.R.A.S.*, xliii. 1, 1881.

the relative brightness of stars deduced from the positions on the wedge at which they become invisible. H. H. Plaskett * has applied the neutral wedge to a photographic study of the distribution of intensity in a star's spectrum ; a wedge *uniformly* illuminated along its length by light from a star is placed in front of the slit and the breadth of the resultant spectrum for different wave-lengths provides a measure of the intensity of the corresponding radiation.

Difficulty in the application of results found by the wedge photometer arises from the fact that the wedge may show a certain amount of selective absorption. This criticism does not apply to the Nicol photometer, at any rate in its latest forms. This type was first designed by Pickering, in 1877 † and was used for the Harvard Photometric Observations. The essential point lies in cutting down by an accurately-known amount the light from a standard source so as to make it equal to that of the source under observation ; this is done by the use of a double-image prism and a Nicol.

During the last three decades photographic photometry has become more and more important. The point of interest lies in the fact that the scale of photographic and photo-visual magnitudes is not the same for all stars. This was only to be expected, as the sensitiveness of the eye and of the photographic plate vary in different manner along the spectrum and the maximum spectral intensity of stars also varies from type to type. The magnitudes, m , of stars on the same photographic plate are given in terms of their diameters, d , quite closely by the empirical formula first adopted at the Royal Observatory, Greenwich, ‡

$$m = a - n \sqrt{d}$$

* *Pub. D.A.O.*, ii. 213, 1923.

† See *Harvard Annals*, xi. 1879, and *Ap. J.*, ii. 89, 1895.

‡ *M.N.R.A.S.*, lii. 125, 1892.

a and n are constants depending on the length of exposure and the nature of the plate. A more accurate instrument for determining stellar magnitudes by photographic methods is the objective-grating first used by Prosper Henry * and Wirtz.† It consists of a series of parallel wires or strips of equal width, separated by equal apertures and stretched across the object-glass of a telescope. The normal star-image is accompanied by a series of diffraction-images, whose magnitudes relative to the central image can be calculated in terms of the optical details of the telescope and the elements of the grating.‡ The auxiliary images are, however, really very narrow spectra and, as the interval between successive images depends on the wave-length of the light, we may, so long as the images are not appreciably lengthened, take the observed intervals as a measure of the wave-length of the brightest portion of the star's spectrum, its so-called "effective wave-length." The chief use of the objective grating has, however, been in the accurate determination of a scale of stellar magnitudes by comparing diffracted images of the brighter stars with the normal images of the fainter stars. Merton§ has suggested an application of the coarse grating, when crossed with an objective prism, to the spectrophotometry of stars in regions of the spectrum where the wedge method fails owing to the light being absorbed by the wedge.

Entirely different principles underlie two modern stellar photometers which must be briefly described. Considerably increased accuracy was obtained by Stebbins in 1910 when he measured the light from a star by the change in the resistance which the light caused, when it fell on the surface of a selenium cell.|| This method has given place

* *Conférence Astrophotographique Internationale de Juillet 1900*, circular No. 8, 41, 1901.

† *A.N.*, cliv. 317, 1901.

‡ *M.N.R.A.S.*, lxxiv. 50, 1913.

§ *Proc. R.S.*, xcix. A, 78, 1921.

|| *Ap. J.*, xxxii. 185, 1910.

to the still more refined and accurate method of measuring a star's brightness by the number of electrons emitted from a small cell of metal photo-electrically sensitive to radiation in the visual region, when the light from the star falls on it.* The cells of different metals, e.g. calcium and potassium, are chiefly sensitive to light from different parts of the spectrum. This property enables us, by studying the effect of a star's light on cells of different metals, to deduce the relative intensity of radiation in different wave-lengths and hence the effective temperature of the star. The question of colour-index is one of the points of contact of photometry with stellar physics proper. We shall see later how closely photometry is bound up with one of the most startling recent developments of the subject.†

Sampson ‡ has made a very promising application of the photo-electric cell to the measurement of relative intensities of lines in a spectrum and also to the variations of intensity of different portions of the continuous spectrum. He passes a beam of light through a spectrogram on to a photo-electric cell, used in the form of a Koch microphotometer, and obtains, clear of personal equation, an accurate measure of the distribution of light with wave-length in the star's spectrum. There are photographic and other difficulties to be overcome, but the method promises results of a much higher order of accuracy than those given by earlier methods. Still another instrument used for studying

* See *Vierteljahrsschrift der Astronomischen Gesellschaft*, xlvi. 210, 1913 (Meyer and Rosenberg), and *A.N.*, cxcvi. 357, 1913 (Guthnick), for early observations. *Ap. J.*, xlv. 69, 1917 (Kunz) and *M.N.R.A.S.*, lxxix. 344, 1919 (Lindemann) and *Lick Obs. Bull.*, No. 349, 1921 (Cummings), give theoretical and instrumental details.

† For a fuller account of photometers, see "An Introduction to the Study of Variable Stars," Caroline Furness (Constable), 1915; also "Einführung in das Studium der veränderliche Sterne," K. Schiller, Leipzig, 1923.

‡ *M.N.R.A.S.*, lxxxiii. 174, 1923, and xxxv. 212, 1925.

stellar radiation is the thermocouple, which was successfully applied to stars by Pfund, in 1913.* Essentially this makes use of the fact that if a circuit consists of two metals, and if the joints are kept at different temperatures, then a current flows through the circuit and a measure of the current allows a determination of the difference of temperatures of the joints. A recent account of the construction of vacuum thermocouples has been given by Pettit and S. B. Nicholson.† The thermocouple can be used with coloured screens to determine the distribution of spectral energy across the sun's disc in different wave-lengths. It can also be used to measure the total radiation from a spot on the sun or from a star. In the latter case, the additional use of a screen, such as a water screen, has led to useful conclusions about the intensities of the infra-red radiations in stellar spectra. Coblentz has applied this method to the long-period variable stars.‡

10 (b). Other Instruments for measuring Radiation.—The bolometer, a sensitive instrument for measuring the distribution of heat in the solar spectrum, was designed and constructed by Langley, in 1880.§ The principle lay in exposing to the source of radiation a small surface, consisting of exceedingly thin strips of platinum. This formed an arm of a Wheatstone bridge. When warmed by so little as 0.0001° C., the resistance of the surface altered sufficiently to produce a measurable deflection in the needle of a galvanometer in the Wheatstone bridge current. In its essentials the instrument was completed by a recording

* *Allegheny Observatory Publications*, iii. 45, 1913.

† *Ap. J.*, lv. 295, 1922. See also Coblentz, *Scientific Papers of the Bureau of Standards*, No. 438, 1922.

‡ See Chapter XII below.

§ *Proceedings of the American Academy of Arts and Sciences*, whole series, xvi. 342, 1881. See also *Professional Papers of the U.S. Signal Service*, No. 15, "Researches on Solar Heat," by S. P. Langley, 1884.

apparatus which showed the deflection of the galvanometer corresponding to a given wave-length in the spectrum. In this way knowledge of the absorption lines in the solar spectrum was extended in the infra-red far beyond the range accessible for study before the bolometer was used. In addition to the bolometer, which gives only relative values for the radiation measured in different wave-lengths, a pyrheliometer is used to determine the absolute scale.* This consists of a thermometer attached to a blackened copper disc, which can be exposed to the shade or the sun at will. Good contact between thermometer and disc is secured by an intermediate film of mercury. This is the instrument used by Abbott in his work on the value and variation of the total amount of solar radiation.

11. Stellar Interferometer.—An instrument has recently been designed at the Mount Wilson Observatory to carry out a suggestion made by Michelson, in 1890 ; † the separation of close binary stars and the angular diameters of star discs are now being measured by means of a stellar interferometer. In its essence this consists of an arrangement by means of mirrors at a controlled distance apart (the first stellar interferometer had a base of 20 feet), which secures that two parallel beams from the star are viewed together in an eye-piece. The two light-paths through the instrument for rays from any point on the star-disc are different. There results in general for the whole star-disc an interference pattern in the field of view ; the fringes only vanish when the angular diameter of the star-disc is a simple function of the wave-length of the star's light (assumed known), and of the separation of the mirrors. An observation of the separation of the mirrors, for which

* See *Annals of the Astrophysical Observatory of the Smithsonian Institution*, ii. 36, 1908.

† *Phil. Mag.*, v. ser. xxx., i. 1890 ; *Ap. J.*, li. 263, 1920, and liii. 249, 1921.

the fringes vanish, leads to the angular diameter of the stellar disc or the angular separation* of the two components of a close binary.* The first star disc was measured by Pease in December, 1920, at Mount Wilson. The star Betelgeuze (α *Orionis*), was found to have a diameter of $0''.045$.† It is not without interest to note that Michelson's original paper led to the development of the objective grating for stellar work, which has been referred to above.

* *Ap. J.*, lvi. 40, 1922. Merrill gives as the average residual 1° for position angle and $0''.0007$ for separation.

† See below, § 38.

CHAPTER III

LABORATORY INVESTIGATIONS

12. Relation to Stellar Physics.—The problems set to the student of stellar physics are first to identify the lines appearing in celestial spectra, and secondly, from an examination of the grouping, the intensities and the structure of these lines, to deduce something as to the physical condition of the outer layers of the stellar atmospheres. The task of identifying the lines and bands in celestial spectra has been steadily and so successfully faced by a succession of researchers in the laboratory that we may expect confidently that before many years are gone those lines which are still of unknown origin (see Appendix VIII), will have been identified. The interpretation of the spectra in terms of physical conditions has, however, only recently been put on a sure footing. Until Bohr's theory of atomic spectra was available to guide the investigator, the chief spectroscopic experiments, which seemed to have a bearing on astrophysics, were too scattered in nature to lead to any satisfactory conclusions. Some of these will be selected for mention below, mainly in order to reflect the early history of the laboratory side of astrophysics. But pride of place must be given to recent experiments on the stimulation of spectra and their explanation in terms of Bohr's theory.

13. Bohr's Theory.—Adopting the Rutherford model for the atom—a central, positively charged nucleus surrounded by a system of electrons rotating about it in certain defined orbits—Bohr postulates that radiation from an atom only

takes place when it changes from one stable or stationary state to another, in which the energy of the atom is less. If E_1 , E_2 are the values of the energy of the atom in the initial and final stages, then the transition is accompanied by a monochromatic radiation of frequency, ν , given by the equation $h\nu = E_1 - E_2$ (h is a known physical constant called Planck's constant). Similarly, if an atom changes from a condition with energy E_2 to one with energy E_1 it will absorb radiation of frequency ν . Each line in the spectrum of an atom corresponds to an energy difference between two possible levels characteristic of the atom. The energy may be drawn from incoming radiation or from the impulse of a colliding electron. By bombarding an atom with electrons moving with selected speeds, Franck and Hertz* were able to confirm Bohr's relations between the frequency of the emitted radiation and the change in the energy of the atom, relations based originally on experiments on the photo-electric effect. The changes of energy correspond in general to the displacement of an electron from one orbit to another in the atom; in a particular case the electron may be driven from its orbit right out of the atom, which is left singly ionized. On the capture of an electron by this ionized atom lines of its typical (or arc) spectrum are emitted, the lines depending on the orbits into which the electron successively in the course of its recapture settles. Now the atom may have had two electrons removed or be doubly ionized. In this case the capture or binding of one electron will lead to the emission of a different set of spectral lines called the second optical spectrum, the spark spectrum or, in the earlier literature, the enhanced spectrum. Similarly, if three (or more) electrons have been lost by the atom, bright lines of the

* For the chief references, see *Phys. Zeitsch.*, xx. 143, 1919. See also "The Origin of Spectra," Foote and Mohler, New York, 1922.

third optical spectrum (or spectrum of higher order) will be obtained on the binding of an electron by the trebly (or more highly) ionized atom. These spectra have been grouped vaguely under the term super-spark spectra. The following notations have been adopted for the different classes of spectra corresponding to atoms ionized by the loss of one, two, three, or four electrons. If an absorption line is due to the loss of an electron by, or its displacement in, a neutral atom of silicon, then the notation Si or Si I is used to indicate the nature and condition of the atom to which the line corresponds; the same notation is used for an emission line accompanying the capture of an electron by a singly-ionized atom. If a line is absorbed by a singly-ionized atom of silicon losing a second electron or having an electron displaced (or emitted by a doubly-ionized atom binding an electron) the notation Si^+ or Si II is used.* Similarly, for doubly and trebly ionized atoms we have Si^{++} or Si III; Si^{+++} or Si IV. Lines of all these four groups have been identified by A. Fowler; all four are present in different stellar spectra. The different degree of ionization of the atom may be taken as an indication of the different amount of excitation to which it is subject, and we may trace this excitation in general to thermal radiation. The classification of spectral lines into series corresponding to different stages of ionization is, therefore, of fundamental importance in the investigation of stellar temperatures.† Of great assistance in this work is the spectroscopic displacement law of Kossel and Sommerfeld.‡ According to this law, the structure of the spectrum of an

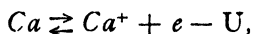
* The notation adopted by Norman Lockyer and other writers— pSi , meaning proto-silicon—was applied to all classes of ionized atoms.

† For experimental work of this nature having direct application to astrophysics, see A. Fowler, *Phil. Trans.*, ccxiv. A, 225, 1914; *Proc. R.S.*, ciii. A, 413, 1923.

‡ *Berichte d. Phys. Ges.*, xxi. 240, 1919.

atom of an element is the same as that of an atom of the following element in the periodic table, the second atom having lost one more electron than the first. Thus the spectra *Na* I, *Mg* II, *Al* III, and *Si* IV have a common structure, and it is possible to use this fact as an aid in classifying the lines due to the more highly ionized atoms of the last-named elements. Another case of similar spectra is that of *H* I, *He* II, which is of considerable historic interest in astrophysics. It was long thought that a series of lines, first found in ζ *Puppis*, were due to hydrogen. It is now definitely established that they are due to ionized helium.

14. Thermal Ionization.—An important step in the application of Bohr's theory to astrophysics was taken by Saha when he applied * the equations of thermodynamics to the study of the ionization of a stellar atmosphere as a function of its pressure and temperature. Assuming that the ionization of a gas—the dissociation of an atom into a positively charged ion and one or more electrons—is essentially of the same nature as a chemical reaction, he considered a reversible reaction of the type—



where *Ca*, *Ca*⁺, *e* are gram-molecules of neutral calcium atoms, singly ionized calcium atoms and electrons respectively and *U* is the work expressed in calories, required to ionize one mol of calcium atoms. Following the methods of physical chemistry,† Saha deduced an equation of the form—

$$\log_{10} \frac{x^2}{1-x^2} P = - \frac{5050 V_i}{T} + 2.5 \log T - S,$$

* *Proc. R.S.*, xcix. A, 135, 1921; *Phil. Mag.*, xl. 472, 809, 1920; xli. 267, 1921; xliv. 1128, 1922. See also Milne, *Observatory*, xliv. 261, 1921; and Russell, *Ap. J.*, iv. 119, 1921.

† See Tolman, *Jour. of the Amer. Chem. Soc.*, xlii. 1185, 1920, and xliii. 866, 1921.

where α = the fractional number of the atoms of the gas which are ionized.

P = the total pressure of the gas.

V_i = the ionization potential of the gas (i.e. the potential through which an electron must drop in order to acquire sufficient velocity to ionize an atom with which it collides), measured in volts.

T = the absolute temperature of the gas.

S = the chemical constant of the electron = 6.69.

Saha pointed out how the percentage ionization depended upon the temperature, the partial and total pressures, and the ionization potential of the gas. Without anticipating subsequent discussion unduly, it may be mentioned here that while Bohr's theory alone leads to such general statements as that the lines of a principal series of a neutral atom should steadily fade with increasing temperature while the lines of the principal series of an ionized atom should rise to a maximum and then fade, Saha's theory leads to an understanding of the different types of spectra found in different layers of the Sun's atmosphere, and to an interpretation of the difference of spectra of giant and dwarf stars. In his theory fresh emphasis has to be laid upon the ionization potential of the element concerned and on the pressure of the atmosphere in different layers of the same star and in stars of different masses and densities. As a typical instance of the kind of laboratory experiment which Saha's theory at once elucidates, we may cite that of Huggins* with regard to the lines of calcium, *Ca* I, 4227 [*g*], and *Ca* II, 3933 [*K*], and 3968 [*H*]. Huggins found that if a spark was taken between two iron electrodes moistened with a strong solution of calcium chloride, the arc line [*g*] weakened much more rapidly than the spark lines [*H*] and [*K*] when

* *Proc. R.S.*, lxi. 433, 1897.

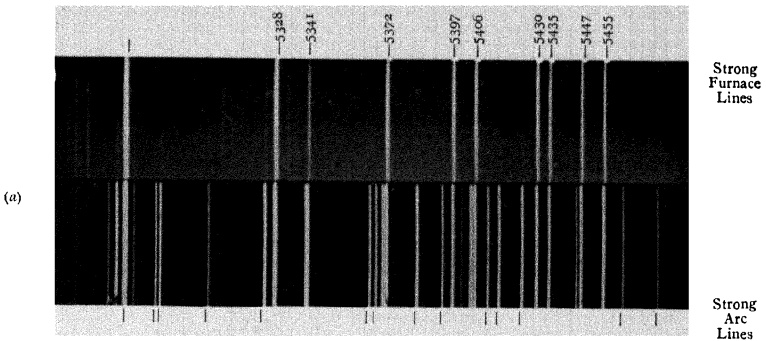
the electrode was washed repeatedly in pure water. Huggins's explanation in terms of vapour density is now seen to be consistent with Saha's general interpretation of such phenomena.

15. Furnace, Arc, and Spark Spectra.—Considerable work has been done in the laboratory during the past forty years in grouping lines according to their relative strength under varying conditions of temperature and electrical excitation. This work was of direct value in connection with the identification of lines in stellar spectra, doubtful identifications being frequently settled through reference to other lines which could be identified with more certainty, and which showed similar behaviour in the laboratory. The early work on enhanced (spark) lines of metals by Norman Lockyer and his colleagues at South Kensington found important applications in the identification of the lines in such spectra as those of novae in their early stages. Here we may mention the early experiments of Liveing and Dewar* who attempted to study the changes in the spectrum of a heated vapour accompanying controlled changes of temperature and without chemical action. The metal to be studied was vaporized inside a carbon tube which was used as one terminal of an arc. King,† at Bonn, and later at Pasadena, carried out numerous investigations, giving for many elements detailed grouping of the spectral lines which strengthen at different stages of excitation. (Plate 7.)

The investigations with the electric furnace extend to temperatures of some 2000° K. In the arc we are concerned with temperatures of about 3100° K. In the spark, though it is difficult to speak of temperature, it is clear that the atoms of the vapour under investigation are subjected to more violent electrical excitation than in the arc. Even in the arc, however, the enhanced lines typical of the

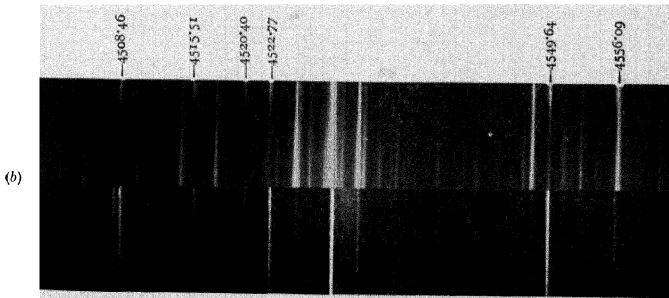
* *Proc. R.S.*, xxxiv. 123, 1882.

† *Ap. J.*, xxi. 236, 1905, and later papers in the *Ap. J.*



SPECTRUM OF IRON IN ELECTRIC FURNACE AND ELECTRIC ARC

Photographed by C. P. Butler at National Physical Laboratory, 1911



ARC SPECTRUM OF IRON. Photographed at Cambridge

SPARK SPECTRUM OF IRON. Photographed at Solar Physics Observatory, London

} showing typical enhanced lines

spark spectrum are found in regions of a high potential gradient, e.g. near the positive pole of a Pfund arc.* In varying ways and by different methods the grouping of complicated spectra have been empirically determined. The main types of spectra can be paralleled in celestial sources. The accurate discussion of the physical condition of the atmospheres, giving rise to these spectra, will become possible as soon as the series relationships of the spectral lines concerned have been established in the laboratory.

16. Pressure and Stark Effect.—Stark † and Lo Surdo ‡ observed, in 1913, that in a strong electric field lines were split into polarized components. So far, no direct instance of Stark effect has been traced in astrophysical spectra. It is, however, possible that the broadening of lines under pressure may be an instance of the Stark effect as also the slight shifts of lines in the direction of greater wave-length observed under pressure by Jewell, Mohler, and Humphreys.§ Strong local electric fields may be set up between atoms close together in the lower layers of a star's atmosphere. It has, indeed, been held that the continuous spectrum of a star is to be traced to the complications in a many-lined spectrum caused by the action of strong local electric fields in broadening the separate lines. Efforts have been made to elucidate the displacements of lines in the solar spectrum in terms of pressure, but it is now generally held that the pressure in the layer where the absorption lines originate is too low (being of the order of 10^{-1} atmosphere or less) for pressure effects to be measurable. There is, however, one effect of pressure which may be reflected in stellar spectra, and that is a change of relative intensity of different lines in

* Merrill, *Ap. J.*, lvi. 475, 1922. See also Plate 7 (b).

† *Sitz. d. k. Preuss. Akad. d. Wiss.*, 1913, p. 932.

‡ *Atti della Reale Accad. dei Lincei, Rendiconti*, xxii. 2, p. 664, 1913.

§ For references see *Ap. J.*, vi. 169, 1897; lvi. 16, 1922.

a spectrum and a tendency in an emission spectrum for lines of higher term number in a series to reverse. A stellar spectrum containing both dark and bright lines of the same spectral series of the same element is suggestive of the spectra found in the laboratory under pressure. Though results obtained under high pressures do not apply directly to astrophysics, we have already seen * that low pressures play an important part in Saha's theory.

17. Zeeman Effect.—The effect of a magnetic field on a spectrum, the discovery of which was announced by Zeeman in 1897,† has, however, important applications in astrophysics. Zeeman detected the widening of a line when the source of the spectrum was subject to a strong magnetic field, and was viewed in a direction parallel to the lines of force. Lorentz, on theoretical grounds, deduced that the widening was due to the addition of two wing lines which should be circularly polarized in opposite directions to each other, and this result was confirmed in the laboratory. The presence of strong magnetic fields in sunspots was first shown by Hale ‡ and connected with vertical currents of charged particles. Later he discovered and made a detailed study of the general magnetic field of the sun, showing that it corresponded fairly closely to that of the earth. Admitting that the field varies with the depth of the gas examined, one can give an idea of its strength by saying that the vertical field at the poles is about 50 gauss, while that of the earth is 0.6 gauss. A typical sunspot field would be about 1000 gauss.§

* § 14 above.

† *Verlagen der Wis en Natuurkundige Afdeeling d. k. Akad. v. Wetenschappen te Amsterdam*, vi. 13, 1897; also *Phil. Mag.*, v. ser. xliii. 226, 1897.

‡ *Ap. J.*, xxviii. 315, 1908.

§ For an account, with bibliography, of the determination of the sun's general magnetic field, see Seares, *Observatory*, xlv. 310, 1922.

18. Chemical Action and Impurities.—The presence of the vapour of a separate gas, whether chemically active or not, may very seriously affect a spectrum. For instance, the hydrogen spectrum, which plays so considerable a part in the classification of stellar spectra, may be reduced in intensity by one-half by the mere introduction of a small quantity of mercury vapour (one molecule in 2500).* Again, Merton and Nicholson have shown † the different kind of effect on the hydrogen spectrum of mixture with helium. They worked with a vacuum tube filled with pure helium at 41 mm. pressure. When a heavy discharge was passed through the tube a very slight evolution of hydrogen took place from the electrodes which had not been completely cleared of hydrogen. Under these conditions, the spectrum of hydrogen predominated, far surpassing the helium lines in brilliance, and the higher members of the important Balmer series of hydrogen lines, so conspicuous in certain celestial spectra and so difficult to reproduce in the laboratory, were seen as well as in any previous experiment. Spectra of a mixture of hydrogen and helium under slightly different conditions, but with a larger proportion of hydrogen present, showed the helium spectrum predominant and the hydrogen spectrum greatly reduced in intensity. Crew ‡ found that if a metallic arc was struck in an atmosphere of hydrogen instead of in air, those lines which were stronger in the spark spectrum of the metal were strengthened in the arc in hydrogen. Hemsalech and de Gramont § have found that the well-known spark line of magnesium λ 4481 can be obtained as a sharp line in a stable arc burning between magnesium electrodes in an atmosphere of nitrogen, with quite low potential gradients. They suggest that in

* Lewis, *Ap. J.*, x. 152, 1899.

† *Proc. R.S.*, xcvi. A, 112, 1919.

‡ *Ap. J.*, xii. 167, 1900.

§ *Phil. Mag.*, vi. ser., lxiii. 843, 1922.

this case some special chemical reaction may be the important factor in the result. •

Another way in which impurities have been shown to affect the presence of enhanced lines in the spectrum of a gas has been demonstrated by King.* If the vapour of an easily-ionized substance, such as potassium, is present in an atmosphere of a less easily ionized substance, such as calcium, the supply of electrons is greater in the mixture under given conditions than it would be in the presence of calcium alone. The proportion of positively ionized atoms of calcium is diminished in the condition of relative equilibrium and the enhanced spark lines are weakened relatively to the lines of the normal atom. Russell has suggested † that this result may account for some puzzling anomalies in astrophysical spectra. Royds has shown ‡ that unsymmetrical lines may be displaced slightly in the presence of impurities. This he also ascribes to changes in the ionization due to the presence of impurities. In celestial spectra, one may count confidently on the presence of mixtures of gases, and it follows that the effects of impurities on spectra must have application in many cases.

Of chemical action there is not much that need be said. Celestial spectra are generally concerned with high temperatures where the spectra of elements and not of compounds are to be expected. Nevertheless, in the solar spectrum, particularly in the spectrum of sunspots, and in the spectra of red stars of low temperature, bands have been observed which are due to compounds. Here we need only refer to magnesium hydride, which gives a band spectrum traced by Liveing and Dewar § to the combination of hydrogen and magnesium and identified by A. Fowler || in the spectrum

* *Proc. N.A.S.*, viii. 123, 1922. † *Ap. J.*, lv. 119, 1922.

‡ *Kodaikanal Obs. Bull.*, No. lxxiii. 1923.

§ *R.S. Proc.*, xxxii. 198, 1881.

|| *Phil. Trans.*, ccix. A, 460, 1909.

of sunspots ; to titanium oxide identified by A. Fowler * in the spectrum of δ Ceti ; to zirconium oxide identified by Merrill † in the spectrum of S type stars ; to the hydrocarbon band—Fraunhofer's [G] band—identified by Newall, Baxandall, and Butler in the ordinary solar spectrum ; ‡ and to a band due to ammonia found by A. Fowler and Gregory in the sun's ultra-violet spectrum.§ Carbon compounds have also been traced in the band spectra of comets and of certain stars, and laboratory work has been necessary to trace the origins of some of these bands. But the extent to which the spectra of compounds enter into astrophysics has been sufficiently indicated, and details can be left for discussion in the sections where they more naturally belong. In this chapter all that need be added is a reference to the thermo-chemical discussion of the pressure of a star's atmosphere in which such a compound as titanium oxide can be present at a temperature of about 3000° K.|| The conclusion is that the partial pressure of the titanium and oxygen together is of the order of 10^{-4} atmosphere. The study of the heat of reaction of compounds throws light on the selection of those found in the cooler stars, those with the highest heats of formation being the most likely ones to appear.

19. Black Body Radiation.—Kirchhoff, in his great memoir on the "Relation between the Emissive and Absorptive Power of Bodies for Heat and Light" invented the term "black body" for a body which, for infinitely small thickness, absorbs all rays which fall upon it. If a hollow body is kept heated uniformly and has a small aperture, the radiation emerging from the aperture approaches that

* *Proc. R.S.*, lxxii. 219, 1904.

† *Pub. A.S.P.*, xxxv. 217, 1923.

‡ *M.N.R.A.S.*, lxxvi. 640, 1915.

§ *Phil. Trans.*, ccxviii. A, 351, 1918.

|| Atkinson, *M.N.R.A.S.*, lxxxii. 396, 1922.

of a black body more and more closely the smaller the aperture. The variation of the black¹ body radiation with the wave-length for different temperatures has been determined by a combination of thermodynamical theory and the quantum theory, and has been verified by Coblentz* and others. The shape of the energy curve and the wave-length of its maximum have been used † to determine the temperatures of stars, the assumption being made that the continuous spectrum is effectively that of a black body. Broadly speaking, the conclusions as to the temperature of the radiating layer of a star, derived by this method, may be accepted.

* *Scientific Papers of the Bureau of Standards*, No. 406, 1920.

† See Chapter VI below.

CHAPTER IV

THE SUN

20. The Nature of the Sun.—The Sun is a body spherical in shape and 1,390,000 km. in diameter ; it lies at an average distance of nearly 150,000,000 km. from the Earth. Its mean density is 1.4, and it contains elements familiar to us on the Earth. Its surface consists of glowing gas at an absolute temperature of about 6500° K.* Storms occur in its atmosphere represented by gigantic outbursts of flaming gas above its ordinary surface and by cyclonic whirls below. The rotation of the surface shows a marked equatorial acceleration. Dark spots, which may be large enough to swallow up the earth many times over, appear in a range of some 30° of latitude on each side of the equator and with a frequency which varies in a principal period of 11½ or 22½ years. Along with periodic changes in the Sun's spottedness come changes in its upper atmosphere, and notably in the tenuous extended atmosphere called the corona, which is only seen at eclipses. The spots are the centres of strong magnetic fields, and the Sun itself has a general magnetic field resembling that of the Earth.

To anticipate later chapters of this book we may add that different layers of the Sun's atmosphere give spectra like those of stars of different spectral classes : its normal Fraunhoferic spectrum is of class G, the spectrum of a higher layer or chromosphere is of class A to F, and that of

* See *Observatory*, xlvii. 160, 1924.

a lower layer or of the sunspots is of class K. The Sun is a dwarf star, rather fainter than the majority of the stars we see, and slightly below the average in mass. It is rather advanced in its evolutionary course, and is at present probably cooling down. It probably forms part of a local cluster moving through the galaxy, its own peculiar velocity being 17.7 km./sec. (See § 45 below as to the exact meaning of this statement.)

The above is a very brief statement of the main details that we know about the Sun. The rest of this chapter will be devoted to developing some of the above statements.

21. The Reversing Layer.—The ordinary absorption spectrum of the Sun, that of the so-called reversing layer, was mapped by Fraunhofer in 1814. Subsequently, measurements of the wave-lengths of the lines were made by Ångström and others, Rowland * publishing, in the years 1895-97, a "Preliminary Table of Solar Spectrum Wave-lengths." This covers a range from 2975 Å to 7331 Å. Outside this range the work has been extended in the infrared by Abney † and by Meggers and Brackett to 9850 Å.‡

From numerous coincidences with lines in the spectra of certain elements, these elements can be safely identified as present in the vapours that give the Sun's absorption spectrum. The list of elements thus identified slowly grows. The work of identification is not easy. Rowland's Tables contain some 20,000 lines, and out of these a single element, e.g. iron, may account for as many as 2000 lines. Again, some elements may be present only in compounds. Thus the laboratory lines associated with pure nitrogen have not been traced, but lines due to bands of cyanogen and ammonia, compounds of nitrogen, have been found in very large

* *Ap. J.*, i.-v. 1895-97.

† *Phil. Trans.*, clxxvii. 457, 1885.

‡ *Allegheny Observatory Publications*, vi. 13, 1919; *Ap. J.*, xlvii. 1, 1918, and liii. 121, 1921.

numbers. Altogether at present the following 66 elements have been identified in the Sun. They are placed in the order in which Rowland placed them, according to the number of lines identified *—the elements after the stroke have been identified later ; they have not all been identified in the Fraunhoferic spectrum, some, like helium, belonging only to the upper atmosphere or chromosphere :—

TABLE I
ELEMENTS IDENTIFIED IN THE SUN

Iron	Barium	Tungsten
Nickel	Aluminium	Indium
Titanium	Cadmium	Bismuth
Manganese	Rhodium	Rubidium
Chromium	Erbium	Dysprosium
Cobalt	Zinc	Gadolinium
Carbon	Copper	Thallium
Vanadium	Silver*	Caesium
Zirconium	Glucinum	Tantalum
Cerium	Germanium	Osmium
Calcium	Tin	Thorium
Scandium	Lead	Lithium
Neodymium	Potassium	Samarium
Lanthanum	-----	Tellurium†
Yttrium	Nitrogen	Platinum†
Niobium	(in compounds)	Uranium†
Molybdenum	Helium	Arsenic†
Palladium	Oxygen	Mercury†
Magnesium	Ruthenium	Praesodymium†
Sodium	Gallium	Thulium†
Silicon	Europium	Terbium†
Hydrogen	Ytterbium	Lutetium†
Strontium	Neo-Ytterbium	

One source of error in identifying elements as present in the Sun must be briefly mentioned. The dark lines of the solar spectrum are produced in the passage of rays from the hot photosphere, which gives a continuous spectrum through the cooler vapours of the "reversing layer," which absorb an appreciable fraction of the radiation of

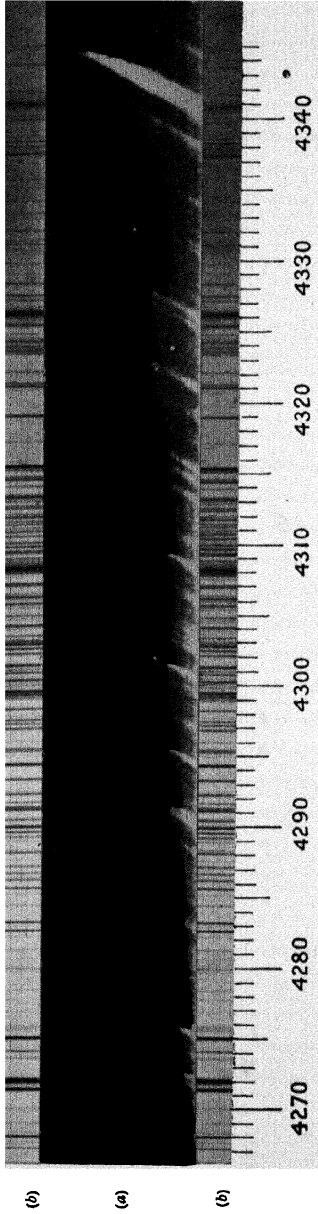
* *American Journal of Science*, xli. 244, 1891.

† Doubtful identifications.

certain definite wave-lengths. But these rays, on their way to the spectroscope, pass through our atmosphere. How are we to tell that the absorption is not all produced in and by the Earth's own atmosphere? One answer comes at once in the differences found in the spectra of different stars. A second answer has been provided by the development of methods for picking out from the Sun's spectrum the lines which are due to the absorption of our atmosphere, the so-called telluric lines. One way is to compare the spectrum of the Sun when high in the heavens—observed especially from the summit of a high mountain such as Mont Blanc—with the spectrum of the Sun when low down—observed at sea-level. The difference in the depth of terrestrial atmosphere through which the light has travelled in the two cases is sufficient to alter considerably the intensity of the telluric lines and enables the investigator to pick them out with confidence. A further check may be supplied by making use of the Doppler effect.* When a mass of gas is moving towards the observer, the absorption lines due to it are all displaced to the violet by an amount which enables the velocity of the gas relative to the observer in the line of sight to be measured: when the motion of the gas is away from the observer the lines are correspondingly displaced to the red. Now the Sun is rotating on its axis and in spectra of the east and west limb of the Sun the lines of solar origin are found displaced to the violet and the red respectively, while the telluric lines are unaffected. Hence a comparison of two solar spectra taken at the east and west limb will, if the dispersion of the spectrograms is sufficient, enable the telluric lines to be picked out with certainty.

The amount of light available in the solar spectrum enables an investigator to use a very high dispersion. Work of very great accuracy can be undertaken. The resultant

* See Chapter VII below.



FLASH SPECTRUM COMPARED WITH FRAUNHOFERIC SPECTRUM

(a) Flash spectrum photographed by H. F. Newall in Sumatra at the Eclipse of 1901, May 17-18, with a 5-inch plane grating mounted as an objective grating. (b) Rowland's map of the solar spectrum

shift of lines, due to motion, pressure, or other causes, can be measured to an accuracy of 0.0005 Å. One of the most important tests of the equivalence hypothesis which underlies Einstein's generalized principle of relativity was provided by a predicted shift of the Fraunhoferic lines to the red by an amount ranging from 0.008 Å at 3790 Å, to 0.014 Å near the red line H α . The evidence is necessarily bound up with that for currents in the solar atmosphere, and with a determination of the pressure of the gases that give the absorption lines. With the general adoption of low values for the pressure of the reversing layer, the controversy over the reality of the Einstein shift of the lines in the Sun's spectrum has ended in its general acceptance.*

22. Higher Layers in the Sun's Atmosphere ; Prominences.

—The reversing layer of whose composition we have evidence in the Fraunhoferic spectrum, extends through several hundred kilometres. Above this layer lies the chromosphere, a layer of very bright gas several thousands of kilometres thick, and consisting principally, at the highest levels at any rate, of hydrogen and calcium. This layer has been studied almost entirely at total solar eclipses. It gives the so-called "flash spectrum" (Plate 8). At the beginning or end of totality, when the Moon just covers the photosphere, part of the chromosphere is left projecting as an arc of varying depth—a greater depth being necessarily visible at the centre of the arc than at the cusps. If this arc is photographed through a prismatic camera, the resulting spectrum consists of a number of bright arcs—one corresponding to each line in the spectrum of the glowing gas of the chromosphere—and the length of the arc seen grows with the height to which the gas which gives the corresponding line extends upward in the chromosphere. The flash spectrum is, for its lower levels, a reversal of the Fraunhoferic spectrum,

* See *Observatory*, xlvii. 9, 1924.

but certain lines, notably the Balmer series of hydrogen, the lines of helium and the enhanced spark lines of certain metals are strengthened considerably and show arcs of increased length, showing that they come from gases which extend to higher levels in the chromosphere. Helium was, in fact, first discovered in the chromosphere, and only subsequently identified by Ramsay in the laboratory.

The most complete list of chromospheric lines was obtained by Mitchell at the eclipse of 1905.* Mitchell gives the intensities of these lines and also, from a measure of the lengths of the arcs corresponding to the various lines, a statement of the height in the sun's atmosphere to which the gas producing each line extends. The vapours of ionized calcium, hydrogen, helium, and various ionized metals extend, in that order, highest above the Sun's limb; the *Ca* II lines [H] and [K], reach a height of 14,000 km., $H\beta$ and $H\gamma$ a height of 8000 km., and the *He* line [D_3] a height of 7500 km. The presence of lines due to the ionized atoms of certain metals has been discussed by Saha † in terms of his application of the thermo-chemical Reaction-Isobar to ionization considered as a case of dissociation. The degree of ionization for any element for a given temperature and pressure is determined by the theory, and on examination of the solar evidence it is found that pressure plays a very important part in determining the relative ionization of the different elements in the high-level chromosphere. The first application of Saha's theory was, in fact, made to the chromosphere, though the theory was subsequently developed and applied successfully to general stellar physics.

Rising out from the chromosphere are the prominences, clouds of flaming gas lying quietly above the chromosphere, or bursting outwards with a high velocity and falling back

* *Ap. J.*, xxxviii. 407, 1913. See also Dyson, *Phil. Trans.*, ccvi. A, 403, 1906.

† *Phil. Mag.*, ser. vi., xl. 472, 1920. See § 14 above.



LARGE SOLAR PROMINENCE

Photographed by A. S. Eddington at Principe at the Eclipse of 1919, May 29. The prominence extended from the east point on the solar equator to 40° S.

again on to the Sun's surface (Plate 9). At first these, too, were only seen at eclipses, but Lockyer and Janssen independently showed, in 1868, that they could be observed at any time.* As they consist mostly of glowing hydrogen gas, it was only necessary to use a spectroscope with rather a wide slit and to observe the spectrum of the limb of the Sun at the red line $H\alpha$. Setting the slit parallel to the limb, the bright line from the prominence could be easily seen against the faint continuous spectrum of the sky background. Hence the height of a prominence at any point of the limb could be measured—or rather the height of the section of a prominence shown by the slit. If the slit was not wide enough to show the whole prominence, successive observations at different distances from the same point on the limb enabled the observer to build up a picture of the whole prominence. Hydrogen, helium, and calcium are the principal elements found in the prominences. The heights of these prominences vary between some hundreds to some hundreds of thousands of kilometres. The quiescent prominences generally consist of hydrogen only. The eruptive prominences often contain also metallic vapours. As their name implies, they suggest the action of some explosive forces. Prominences have been followed to a height of 830,000 km. above the Sun's surface; † at such great heights they usually show as bright clouds broken clear from the links which, at first, connect them to the solar disc. The present evidence about the velocities with which these eruptive prominences rise from the Sun's limb well justifies the use of the word eruptive. The velocity seems to remain constant for a considerable time, and

* *C.R.*, 26th Oct., 1868. The idea of the method was due to Lockyer. Janssen was the first to apply it successfully. His success and Lockyer's were announced at the same meeting of the Académie des Sciences.

† *Ap. J.*, liii. 310, O. J. Lee.

then suddenly to increase. The discontinuity in the upward velocity may be observed more than once in the growth of a prominence, and suggests a series of internal explosions or the sudden passage from one layer of the solar atmosphere to another of lower density showing less resistance to motion.

The principle employed by Lockyer and Janssen in building up pictures of prominences underlay the development of the spectroheliograph (see Chapter II above), which, in the hands of Hale, has added so much to our knowledge of the Sun's upper atmosphere. It had been known from Young's visual observations that the dark [H] and [K] lines of calcium were sometimes brightly reversed in the neighbourhood of spots. The spectroheliograph, which enables the Sun's disc to be photographed in monochromatic light, was first successfully applied to the photography of the luminous calcium clouds or flocculi and, in fact, to the distribution of the calcium vapours over the whole disc (Plate 10). (Naturally, it also gave a simple means of photographing the prominences in light of a given suitable wave-length in full sunlight.) The spectroheliograph also led to a more detailed knowledge than the simple distribution of bright calcium clouds over the disc. Deslandres pointed out that the structure of the calcium lines [H] and [K] was complex. On a broad, dark line [K_1], there was superposed a bright, central portion [K_2], which was again crossed by a narrow, central, dark line [K_3].* Now, laboratory results † support Deslandres' view that these three portions [K_1], [K_2], and [K_3] belong to vapours of diminishing density and, therefore, presumably to vapours at increasing heights. If, then, using a large dispersion, we set the second slit of the spectro-heliograph to catch the light in turn from [K_1], [K_2], or [K_3] only, we

* [K_2] has been found in 12 stars also and [K_3] in 2 stars; see § 60 below.

† Huggins, *Proc. R.S.*, lxi. 433, 1897.



(c)

(b)

(a)

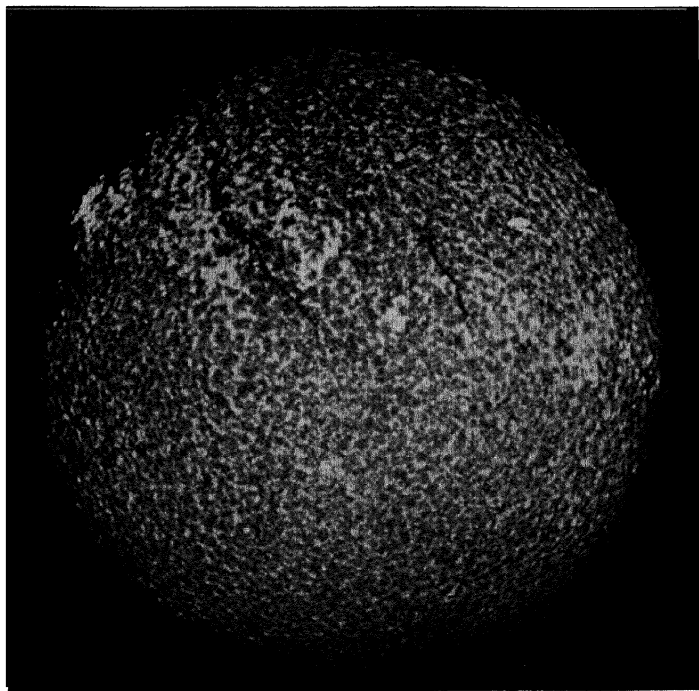
SEPARATION OF THREE LAYERS OF CALCIUM VAPOUR

Spectroheliograms obtained at Meudon by H. Deslandres, 1908, September 7, with a 3-prism spectroheliograph of 14 m. and a second slit of width 0.025 mm. = 0.02 A. at $[K_2]$

(a) Slit at $[K_{3a}]$.

(b) Slit at $[K_{2a}]$

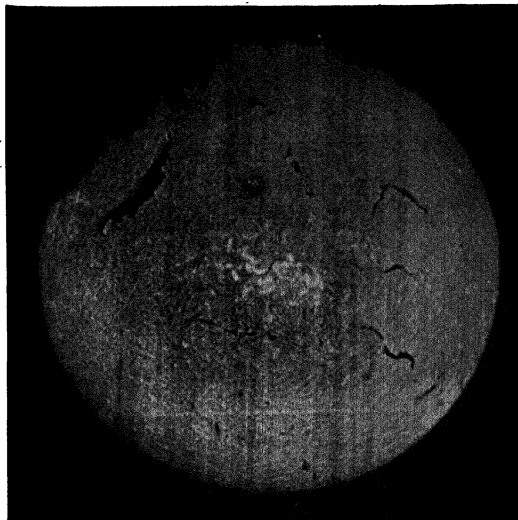
(c) Slit at $[K_{1a}]$



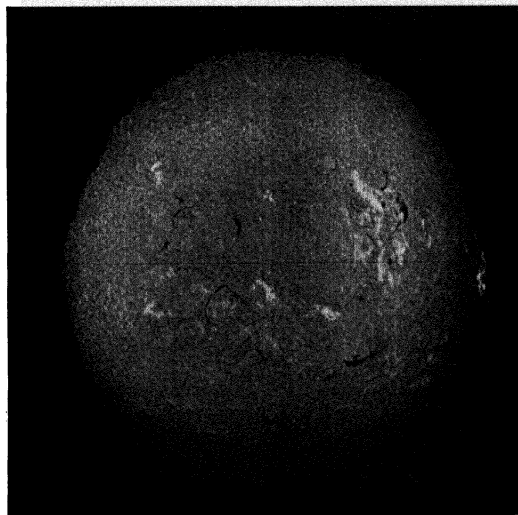
SPECTROHELIOGRAM OF THE SUN IN THE HIGHEST LAYER OF
CALCIUM VAPOUR

Taken by H. Deslandres at Meudon, 1922, May 25, with a 3-prism spectroheliograph, second slit at $[K_2]$ of width 0.07 mm. $\approx 0.13\text{\AA}$. Diameter of original = 86 mm.

(a)



(b)

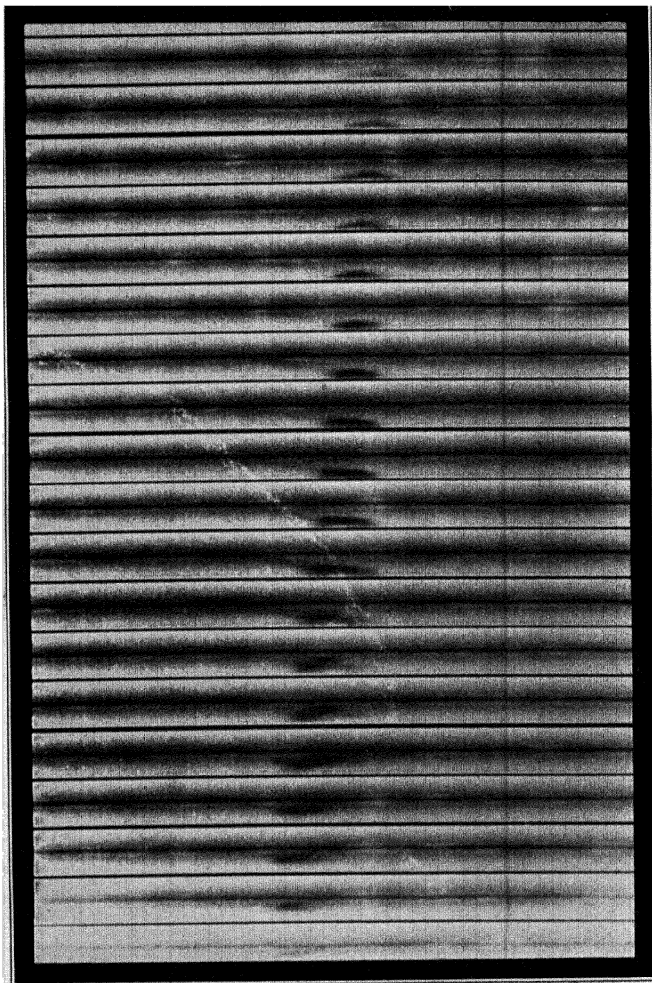


SPECTROHELIOGRAMS OF THE SUN IN THE HIGHEST LAYERS OF
HYDROGEN VAPOUR

Taken by H. Deslandres at Meudon in the first order of a grating spectroheliograph, with the second slit at the centre of Ha

(a) 1910, March 21. Width of second slit 0.065 mm. = 0.39 A. (The marking just above the centre of the disc is a defect in the original plate)

(b) 1919, June 7. Width of second slit 0.09 mm. = 0.53 A.



PORTION OF AN IMAGE OF THE SUN FORMED IN SUCCESSIVE STRIPS BY THE
"SPECTROENREGISTREUR DES VITESSES" OF H. DESLANDRES, MEUDON

The displacement of the dark line to the violet, due to the upward motion of a mass of absorbing gas, is well shown. This filament would be invisible in a spectrohellogram

can get pictures of the Sun in the light from ionized calcium vapours at three different heights of the Sun's atmosphere corresponding to the reversing layer, the chromosphere and the prominences. These pictures differ considerably, notably in the neighbourhood of spots and prominences (Plate 10). Special attention has been paid by Deslandres at Meudon to the upper layers, both of the hydrogen and calcium vapours, and to the dark filaments which spectroheliograms show in these upper layers—high masses of hydrogen or calcium gas which, on the limb, are seen as prominences (Plates 11, 12. See also, Plate 15). By means of the *spectro-enregistreur des vitesses* or velocity recorder (see § 7 above), he has also inquired into the up and down velocities of these higher vapours and their relation to the general circulation in the Sun's atmosphere (Plate 13). One more general remark has to be made about the spectroheliograph pictures. While the calcium flocculi given by $[K_2]$ are bright, the hydrogen flocculi are, in general, dark,* resembling more the $[K_3]$ filaments (Plate 14).

23. Corona.—Stretching far beyond the chromosphere and prominences, extending, it may be, thirteen million kilometres from the limb or even more, there may be seen, at times of total eclipse, a pearl-coloured atmosphere. This is known as the corona. The total light given by it is about half that of the full moon.† The shape of the corona depends upon whether the Sun is near a maximum or minimum phase of spot-frequency (see § 25 below). At spot minimum there are to be seen near the Sun's poles, short, fine rays or streamers, while broad bands of light

* For an account of Hale's work with the spectroheliograph, see "The Study of Stellar Evolution," by G. E. Hale (Chicago, 1909). Also *Publications of Mt. Wilson Observatory, passim*. Deslandres' work is given in *Annales de l'Observatoire d'Astronomie Physique de Paris sis Parc de Meudon*, Tome iv. 1910.

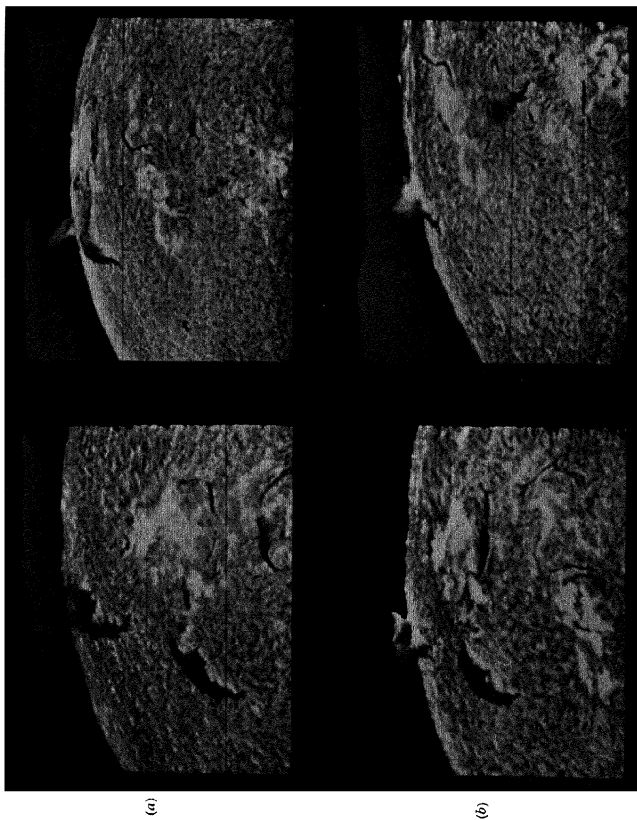
† Kunz and Stebbins, *Ap. J.*, xlix. 151, 1919.

sweep out from the equatorial regions to a much greater distance. Neither set of streamers is radial nor straight, and the boundary between the two sets is well defined, generally about 30° from the poles. At spot-maximum the distribution of the streamers round the disc is much more uniform, and the corona does not extend so far in any direction as the equatorial portions of the minimum corona (Plate 15).

The spectrum of the corona is a blend of several types. There is a continuous spectrum with dark absorption lines probably due to reflected sunlight—polarization tests support the view that a large portion of the coronal light is scattered solar light. There are also, in the lower layers, a number of bright lines due to some unknown element or elements—presumably gases in a state of extreme tenuity. J. W. Nicholson showed that the wave-lengths of the lines of this spectrum could be connected together by a set of simple numerical relations.* He deduced them from the dynamical vibrations of two model atoms with nuclear charges of $+5e$ and $+7e$, which he called protofluorine and coronium respectively. In his theory, the nucleus of the atom is surrounded by a single ring of electrons each of charge $-e$ rotating round the nucleus. The periods of transverse vibrations of such an atom were examined by Nicholson, and he obtained a very simple formula relating them to one another. Series of lines were obtained, such that the cube roots of the wave-lengths in any one series formed an arithmetical progression, while the wave-lengths of members of one series were in a constant ratio to those of the corresponding members of others. Thus,

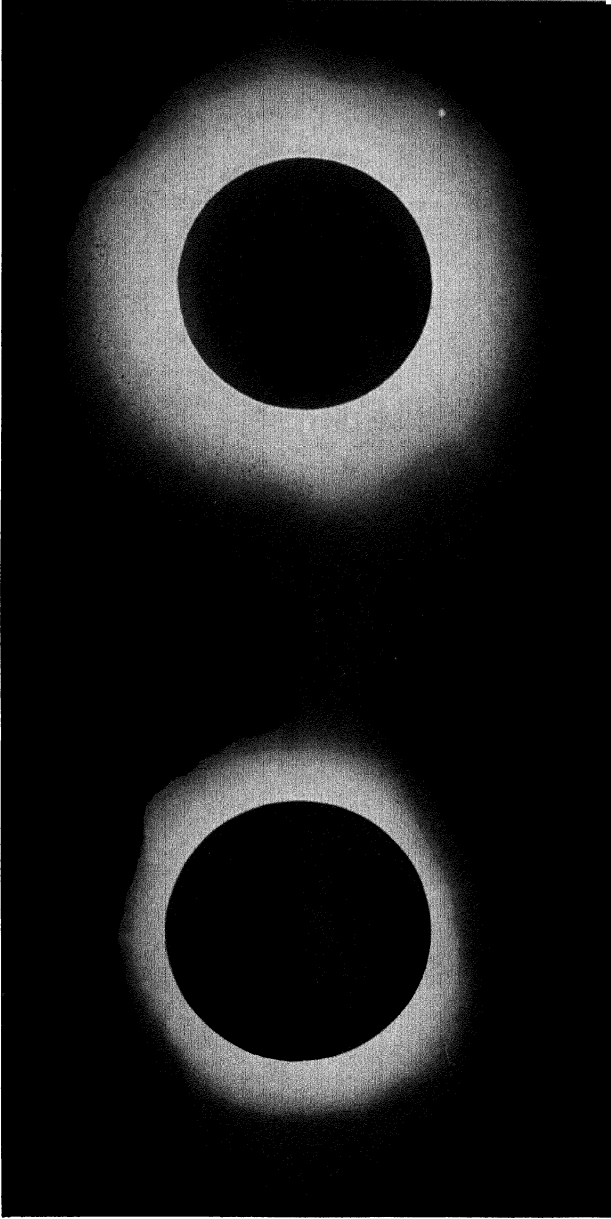
$$(5303\cdot3)^{\frac{1}{3}} - (4359\cdot0)^{\frac{1}{3}} = (4359\cdot0)^{\frac{1}{3}} - (3534\cdot0)^{\frac{1}{3}} = (3534\cdot0)^{\frac{1}{3}} - (2820)^{\frac{1}{3}} = 1\cdot103.$$

* *M.N.R.A.S.*, lxxii, 1911, and lxxvi, 1916.



SPECTROHELIOGRAMS (WITH THE SECOND SLIT IN THE CENTRE OF THE $H\alpha$ LINE) OF
THE WESTERN LIMB OF THE SUN

Obtained by F. Ellerman on (a) June 27, (b) June 28, (c) June 29, 1917, with the 13-foot spectroheliograph of the Mount Wilson Observatory. They illustrate how the hydrogen prominences projected dark on the disc become bright on the limb



(a)

PHOTOGRAPHS OF THE CORONA: (a) AT MINIMUM; (b) AT MAXIMUM

(a) Photograph by H. F. Newall in Sumatra at the eclipse of 1901, May 17-18

(b) Photograph by H. F. Newall at Guelma at the eclipse of 1905, August 30

The lines 5303.3, 4359.0, 3534.0 were known lines ; the line 2820 is too far in the ultra-violet to be observed. However, it fits into Nicholson's scheme of the coronal wave-lengths for the two known lines 4566.0, 3642.5 should form part of a second series of lines whose wave-lengths are in a constant ratio to the above series ; and we have

$$\frac{4566.0}{3534.0} = \frac{3642.5}{2820.0} = 1.292.$$

Or, again, we have

$$(3891)^{\frac{1}{2}} - (3602.3)^{\frac{1}{2}} = (3602.3)^{\frac{1}{2}} - (3328.2)^{\frac{1}{2}} = 0.399$$

$$\text{and } (5535.8)^{\frac{1}{2}} - (5117.7)^{\frac{1}{2}} = (5117.7)^{\frac{1}{2}} - (4722)^{\frac{1}{2}} = 0.457.$$

$$\text{while } \frac{3602.3}{5535.8} = \frac{3328.2}{5117.7} = 0.6508.$$

Nicholson's investigation was made at a time when Bohr's theory of atomic spectra, that radiation could not come from mere dynamical vibrations in the atom, was in process of being established. Hence, although his series relations tied up the whole of the known coronal spectrum into two families of lines, his work has been generally overlooked by physicists. That the series relationships represent something real, even though the models from which they were derived may have to be abandoned, was strikingly confirmed at the eclipse of 1914 by the discovery in the coronal spectrum of a new line in the red at 6374.5*. This line fitted into the first of the above-mentioned series since

$$(6374.5)^{\frac{1}{2}} - (5303.3)^{\frac{1}{2}} = 1.103.$$

These series, for which $\lambda = a(n + \mu)^2$ where n is an integer, remain isolated, not paralleled by any laboratory spectral series. The key to the physical conditions of their appearance has not yet been found.

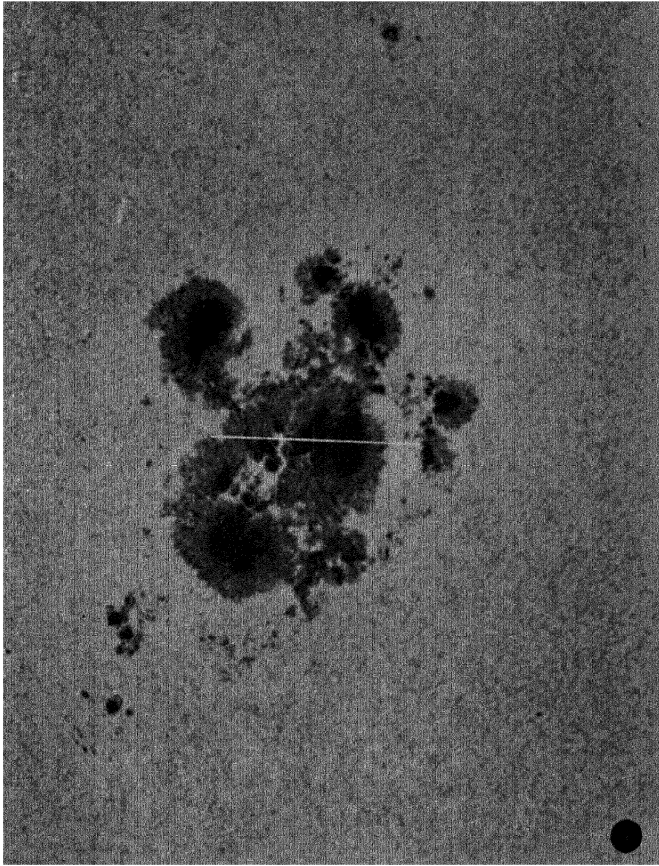
* *C.R.*, clix. 791, 1914, and see § 65 below.

24. Sunspots.—In 1610 Galileo discovered by the aid of the newly-invented telescope the presence of dark spots on the Sun's surface. Though naked-eye spots had been recorded in China for some 1400 years this discovery, new to Western minds, was received at first with hostile incredulity; it was, however, confirmed in due course, and the sunspots have proved a fruitful source of information as to the Sun. The spectrum of the spot differs from that of the Fraunhoferic spectrum. The presence of bands, due to compounds, such as magnesium hydride, and the increased strength of certain low-temperature arc lines, such as those of vanadium, suggest that the spot is at a lower temperature than the reversing layer.* The sunspot spectrum is the same as that of the stellar class Ko, while the Fraunhoferic spectrum is of class Go. Frequently broad absorption lines are found reversed over spots indicating the presence of hot masses of prominence matter above the spot. This presence of prominences over certain spots can be verified by examining the limb of the Sun as the spot reaches it. Evershed,† by spectroscopic observation of spots well away from the Sun's central meridian, discovered that at lower levels the spot umbra showed a flow out from the centre along the disc. St. John confirmed this, and amplified the result by showing ‡ that there was an inward flow at the higher levels, and that the difference of velocity of flow at different levels provided a means of plumbing the depth of the solar atmosphere and of deciding at what depth individual absorption lines originated. These discussions of level for different lines agree with the changes in the magnetic field in a sunspot at varying depths, with the corresponding spectroscopic values

* For a discussion of the lines affected in sunspots, see W. Mitchell, *Ap. J.*, xxii. 4, 1905.

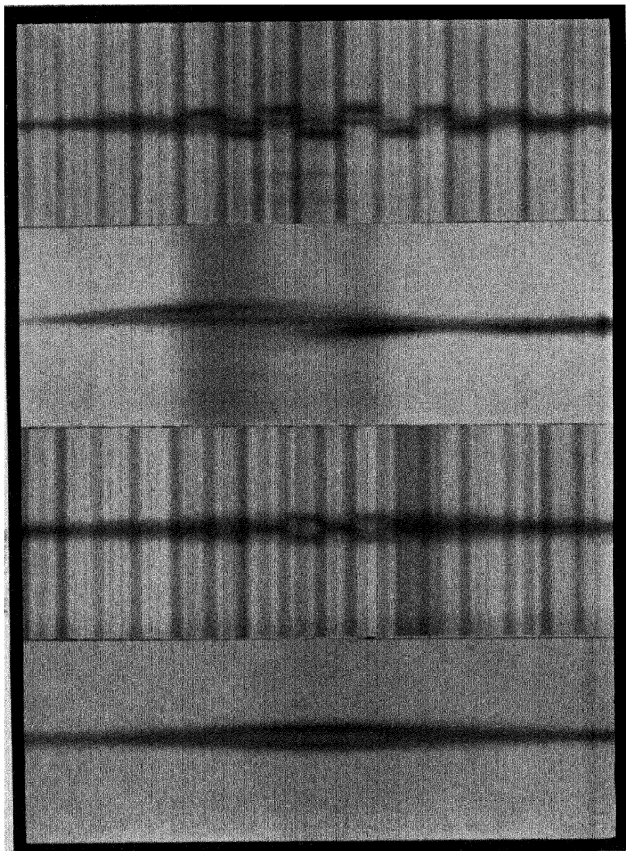
† *M.N.R.A.S.*, lxi. 454, 1909, and lxx. 217, 1910.

‡ *Ap. J.*, xxxvii. 322, and xxxviii. 341, 1913.



GREAT SUN-SPOT GROUP, 1917, AUGUST 8

Photographed at Mount Wilson Solar Observatory. The disc in lower left-hand corner represents the relative size of the Earth. The white line gives the position of the slit used for Plate 17



(d)

(c)

(b)

(a)

IRON TRIPLET AT 6173 Å

In spectrum of spot indicated by white line in Plate 16 showing reversal of circularly polarized light, (a) and (b), plane polarized light of spot near Sun's limb taken with nicol and (α = single, θ = compound) quarter-wave plate; (c) and (d), circularly polarized light of spot near centre of Sun, taken with nicol and (e = single, d = compound) quarter-wave plate

for the solar rotation and with the relative intensities of the lines, weaker lines originating from lower levels.

It had been long known that a general broadening of lines was characteristic of sunspot spectra. It was Hale, who, in 1908,* discovered that one of the chief factors in producing this broadening was the presence of a strong magnetic field in the sunspot. Polarized components, such as Zeeman had found in the laboratory, were shown by means of a nicol prism to form part of the broadened lines. Observations pointed to a magnetic field in the spot radial to the Sun and increasing with the depth (Plates 16, 17). The magnitude of the field—running up to 3000 gauss in exceptional cases—and its polarity have been examined for many spots. The magnetic fields have also been used by Hale † for the detection of spots not found by the ordinary photographic methods. Local magnetic fields have been detected by their Zeeman effect, and it has become possible to trace the life-history of a spot or spot group through a longer period than had hitherto been possible from visual or photographic observations alone. The magnetic fields in spots have been attributed to the vortical motion of negatively-charged particles; this explanation is suggested by pictures of spots obtained with the spectroheliograph. The polarity of the spot fields exhibits some unexplained phenomena; two or three facts of importance stand out. There is a very strong tendency for leading spots of groups in the northern and southern hemispheres of the Sun to show opposite polarity: again, spots occurring in pairs, as they do quite commonly, show in general opposite polarity, the polarity of the western or leading spot agreeing in general with that of single spots in the same hemisphere. It is as though the spots are the open ends of a vortex filament lying mainly inside the Sun. It

* *Ap. J.*, xxviii. 315, 1908.

† *Proc. N.A.S.*, viii. 168, 1922; *M.N.R.A.S.*, lxxxii. 168, 1922.

is probably a fact of prime importance that at the spot-minimum of 1912 it was found that the general polarity of the leading spots in the northern and southern hemispheres changed sign.* After 1912 the normal polarity of the leading spot in the northern hemisphere corresponded to that of the northern magnetic pole of the Earth. No change of polarity occurred at the following maximum, but at the minimum of 1923 a second change of polarity was discovered.† If, as seems likely, a general change of polarity occurs at each minimum, we may have a valuable clue towards the explanation of some of the puzzling phenomena of solar periodicity.

Hale ‡ has suggested that a suitable classification of spots would be in terms of the number of spots in a group and their magnetic polarity. The double or bipolar spot in which we have two principal spots of opposite polarity, the leader representing the normal polarity for its own hemisphere, is the commonest type of spot. There may be a stream of small spots joining them and these, normally but by no means always, show the same polarity as the nearest larger spot. The "trailer" or following spot tends to be further from the Sun's equator than the leader; this tendency increasing with the latitude. In addition many spots appear to be unipolar, that is, they consist of single spots or groups of small spots with the same magnetic polarity. Some of these show small companions of opposite polarity, thus linking on to the ordinary bipolar systems. A further study of magnetic fields in the neighbourhood of unipolar spots may well reveal that they are essentially like the bipolar spots, only some disturbing cause has masked the one end of the vortex from appearing as a visible spot. In this connection a study of the changes

* *Ap. J.*, xlix. 174, 1919.

† Hale, *Proc. N.A.S.*, x. 53, 1924.

‡ *Ap. J.*, xlix. 170, 1919.

in the strength of the magnetic field of a spot before and after its birth and during its subsequent growth and decay should give very valuable information as to the formation of Sun spots. Fox* has examined the differential motion of the calcium flocculi which always surround spot areas. He finds evidence of rotary motion round the spots, but no simple connection with the observed polarity of the magnetic fields of the spots. For the period 1903-8 he found that about single spots and the following members of bipolar spots the motion was anti-cyclonic, i.e. opposite in sense to the rotation of the Sun on its axis. The motion was cyclonic about preceding members of bipolar spots.

Spot groups are generally inclined to the equator, the leading or westernmost spot being nearest to the equator. The inclination of the axis of the group to the equator increases regularly with the latitude. This alignment of the spot groups must be connected with the equatorial acceleration in the Sun's rotation (see § 26 below). Butler † has discussed the position of the axes of elongated patches of calcium flocculi. He finds a similar tendency for them to be inclined equatorward to the west in both the northern and southern hemispheres.

25. Periodicity.—That the outermost layers of the Sun undergo marked changes from time to time has been mentioned above in the paragraph on the corona. These changes are correlated with much more easily examined variations in the proportion of the solar surface that is covered by spots. It was Schwabe of Dessau who, by counting the number of spots, first made it clear that the spot frequency fluctuated regularly in a period of about 10 years.‡

* *Pub. of the Yerkes Observatory*, iii. 162, 1921.

† *M.N.R.A.S.*, lxxxii. 334, 1922 ; lxxxiv. 134, 1924.

‡ *A.N.*, xx. 283, 1843.

Wolf and Wolfer, of Zurich, investigated the early sun-spot records and derived a value for the main period of $11\frac{1}{3}$ years. Wolfer's table, brought up to date, is given below, in Appendix VII. Subsequent work and data have led to the revised value of $11\frac{1}{3}$ years. Careful analysis of the data suggests subsidiary periods, of which the most important are $33\frac{1}{3}$, 8.36, and 4.76 years. The principal periods are, apparently, all sub-multiples of the longest period, $33\frac{1}{3}$ years. A bold attempt was made by Turner to connect this with the period of the Leonid meteors; though his evidence was not conclusive the suggestion, which originated with Sir John Herschel, that we must look outside rather than inside the Sun for an explanation of its periodicity must be borne in mind as possible. Phenomena such as the varying brightness of Encke's comet at different returns and magnetic disturbances on the Earth indicate that phenomena at points remote from the Sun are, at any rate, closely correlated with the solar periodicity.

In each hemisphere, after a minimum, the spots first reappear in high latitudes—in belts about 30° from the equator—and steadily appear nearer to the equator as the maximum approaches; the northern hemisphere becomes active before the southern hemisphere. The outburst dies out as the latitude of the spots reaches an average value of about 8° . Though the zone where spots are appearing moves during the cycle towards the equator individual spots do not drift towards the equator. There is some evidence, however, that individual bright faculæ actually move away from the solar equator.* The rise to a maximum of spottedness is more rapid than the subsequent fall to minimum, the rise taking about 4 years and the fall 7 years. Changes in the distribution of the prominences in latitude accompany the solar period, the relative frequency of prominences in

* *M.N.R.A.S.*, lxxxv. 191, 1924.

high latitudes increasing towards a solar maximum. The corresponding changes in the form of the corona have been mentioned in § 23 above.

Very closely connected with the sunspot frequency are curves for the fluctuations of the terrestrial magnetic elements—the intensity of the Earth's field increasing with the spot frequency. Some connection, the exact nature of which is not known, also exists between disturbances on the Sun and magnetic storms and auroræ on the Earth. The chief point of interest lies in the recurrence of magnetic storms after an interval of 27·3 days—the synodic period of the spot zones: it is as though a storm arises when the Earth enters a beam of charged particles coming from a particular point on the Sun and is repeated 27·3 days later when the Earth occupies effectively the same position relative to the Sun.

26. Solar Rotation.—The Sun's surface does not rotate with the same angular velocity in all latitudes, nor do different layers in the same latitude rotate with the same velocity. As is also the case for Jupiter, there is an equatorial acceleration in the rotation of the Sun, the speed of angular rotation increasing as the latitude decreases. The high-level lines show the most rapid rotation for any given latitude and at the same time they show the least equatorial acceleration. Thus Adams found from the H α line that the daily angular velocity for high-level hydrogen was 15·0° at the equator, and 14·6° at latitude 30°.* For the reversing layer he got corresponding values 14·5° and 13·7° and for spots the values are 14·4° and 13·7°. The simplest expression for the daily angular velocity in terms of the latitude ϕ , appears to be of the form $a + b \cos^2 \phi$; this form is due to Faye, though Carrington

* Adams, "An Investigation of the Rotation Period of the Sun," *Carnegie Institution Paper*, No. 138, 1911.

first derived from observations an approximate law, his law involving $\sin^2 \phi$.* The law in use is empirical, and its form is unexplained as, in fact, is the equatorial acceleration itself. It is by no means certain that the coefficients a and b in the formula are constant even for a given depth and for given lines in the spectrum. As already stated, they differ for different levels of the solar atmosphere. A tabular statement for all determinations has been given by Fox; † from his tables the following average results for the daily motion may be derived:—

H α	$13^{\circ}.6 + 1^{\circ}.4 \cos^2 \phi$
Faculae and flocculi	$11^{\circ}.9 + 2^{\circ}.6 \cos^2 \phi$
Sunspots	$11^{\circ}.6 + 2^{\circ}.8 \cos^2 \phi$
Reversing layer	$11^{\circ}.0 + 3^{\circ}.2 \cos^2 \phi$

Newall has suggested ‡ that a reason why solar activity after a minimum recommences in middle latitudes and spreads towards the equator is to be found in turbulence arising from the velocity gradient in latitude. At low and high latitudes the velocity gradient is low. The retardation accompanying turbulence would increase the difference between the motion of a layer and of the neighbouring layer on the side towards the equator, and hence the tendency for the disturbance and its accompanying vortices to spread towards the equator.

27. Magnetic Field of the Sun.—As in the case of the Earth, the Sun has a general magnetic field which resembles roughly that of a uniformly magnetized sphere. This field, though small, being of the order of 20 gauss, has been detected and measured.§ Its origin is unknown; there are

* "Observation of the Spots on the Sun," R. C. Carrington, 1863.

† *Pub. Yerkes Observatory*, iii. Part III, 1921.

‡ *M.N.R.A.S.*, lxxxii. 104, 1921.

§ For an account of this work and a good bibliography, see Seares, *Observatory*, xliii. 310, 1920.

difficulties in the way of attributing it to the convection of electric charge: enormous electric fields in and near the Sun would be required, and these must be ruled out. The polarity of the field is in the same sense as that of the Earth, the magnetic north pole being near the Sun's northern pole of rotation.

The Sun's magnetic axis makes an angle of 6° with its axis of rotation. The magnetic field is only measurable through a very thin shell of the Sun's atmosphere, and in that shell, as in the case of sunspots, it increases with depth, the value ranging from about 10 to about 50 gauss in a depth of 200 km.

28. Temperature and Radiation.—The radiation from the Sun has been exhaustively studied in order to fix the temperature of the Sun. The two main lines of study have been a quantitative study of the total integrated radiation, and a qualitative examination of the distribution of radiation, particularly of the wave-length of maximum radiation. Corrections have to be very carefully worked out to allow for the absorption of the Earth's atmosphere. When these corrections have been applied it is found that the Sun does not radiate exactly like the laboratory black-body * by comparison with which its temperature is to be decided. It follows naturally that different methods of determining its temperature give different results. Wilsing's figures † may be given as typical of them. For the photosphere he estimated that the absolute temperature varied from 5400° K for the upper layers, to 7000° K for the lowest layer from which radiation reached us. As a round figure, 6500° K may be remembered as representing the Sun's surface temperature. Of the temperature at any considerable depth we know nothing at all certain, although it is safe to assert that it

* See § 34 below.

† *Potsdam Pub.*, xxiii. No. 72, 1917.

is higher, and in all probability it is very much higher than in the photosphere.

The black-body temperature given by light from the centre of the Sun's disc is higher than that given by light from the darkened limb. At the centre where we view the Sun in the direction of its radius the radiation comes from a greater average depth than at the limb. It is of greater intensity, especially in the light of shorter wave-lengths; and the ratio limb/centre examined for different wave-lengths shows that the temperature of the surface which we see at the limb is some 15 to 20 per cent. lower than that of the mean depth to which we see at the Sun's centre.

A study of the Sun's radiation and absorption spectrum leads to the following description of the solar atmosphere.* The gases of the chromosphere are held up by radiation pressure acting on individual atoms, the pressure at the base of this deep layer being of the order of 10^{-7} atmosphere. At the bottom of the chromosphere gravity becomes predominant in deciding equilibrium, there is a rapid increase of pressure with depth. This is the reversing layer which is at an average temperature of 5000° K. In quite a short distance, 200 to 300 km., the pressure increases to about 10^{-2} atmosphere, the opacity increases rapidly, and we pass to the opaque photosphere, the transition being rapid enough to give the observed sharp limb of the Sun. St. John has gone further and drawn up a tentative scheme involving not only pressures at different depths but also the accompanying circulation in the Sun's atmosphere.†

The best measure of the radiation received by the Earth from the Sun is the following: if a surface of one square centimetre is exposed outside the Earth's atmosphere perpendicular to the Sun's rays and at the Earth's mean distance

* Russell and Stewart, *Ap. J.*, lix. 208, 1924.

† *Ibid.*, lx. 39, 1924.

from the Sun, then enough radiant energy from the Sun would cross it in a minute to raise the temperature of a gramme of water by about $1^{\circ}.94$ Centigrade. This figure is called the solar constant.

Abbott, who has done the most recent work * on this question at several stations maintained by the Smithsonian Institution of Washington, found that the solar radiation varied slightly from causes lying outside the Earth's atmosphere. In his view the Sun is a variable star with small, irregular fluctuations in its radiation, due, possibly, to solar radiation being unequal in different directions. A study by Guthnick † of the reflected light received from the planet Saturn failed to confirm Abbot's result. But Abbott, with the aid of observations at two stations (Mount Harqua Hala, Arizona, and Montezuma, Chile), over a period of a year, confirmed the variation of the Sun's radiation ‡ and added the following general rules connecting this variation with changes on the Sun's surface. The value of the solar constant increases with increased sunspot activity, as evidenced by the formation of new spots and the growth of spots, though it may drop when a sunspot group crosses the central diameter of the Sun's disc. The value of the solar constant declines steadily in a long quiescent period of solar activity.

* See *Annals of the Astrophysical Observatory of the Smithsonian Institution*, iv. 1922.

† *A.N.*, ccv. 113, 1917.

‡ *Report on the Astrophysical Observatory of the Smithsonian Institution for 1923*, 109. See also *Proc. N.A.S.*, ix. 194, 1923.

CHAPTER V

THE SOLAR SYSTEM

29. The Aurora.—The existence of a connection between solar disturbances and the earth's magnetic field was mentioned in the previous chapter. An examination of the phenomena of magnetic storms confirms the view based on other observations that there is an ionized layer in the upper atmosphere of the earth. Variations in this ionization are supposed to be due to charged particles coming from outside, and presumably for the most part from the sun. The most obvious sign of this lies in the luminosity produced in the aurora. The delicate draperies, consisting of straight-line streamers ending on the lower side in sharp, bright boundaries are what might be expected if we had ionized clouds of gas coming into the earth's atmosphere along paths determined, in part, by the earth's magnetic field.

Auroral streamers have been traced up to heights of 600 km., but the height of the lower boundaries—generally 85 to 160 km.*—is of more importance to us. For, if the auroræ are, as seems most probable, caused by penetrating beams of charged particles, then we may learn something of the density and constitution of the upper atmosphere from the distance to which the beams penetrate. Lindemann† has deduced from the auroræ that there is very little hydrogen present in the auroral regions and that the predominant gas there is helium with a small admixture of nitrogen. The spectrum of the aurora certainly shows no sign of hydrogen,

* Wright, *Observations on the Aurora*, 30, 1921.

† *Phil. Mag.*, xxxviii. 680, 1919.

but it does give the negative band spectrum of nitrogen.* As is to be expected from the assumed cause of the auroral luminosity, the gases whose presence is revealed by spectroscopic analysis of the auroral light are the gases of our own atmosphere.

The most prominent line generally in the auroral spectrum is a line of unknown origin in the yellow-green at $5577\cdot350$ I.A.† The rest of the spectrum was found by Rayleigh ‡ to consist of the negative-band spectrum of nitrogen, the strongest bands being at $\lambda\lambda 3914, 4278$. Vegard § adds three unknown lines at $\lambda\lambda 4182\cdot5, 3432\cdot7,$ and $3208\cdot3$. The auroral line can always be found on spectrograms obtained on plates exposed to the night sky: Campbell first noted this fact and Slipher found the line on every one of a hundred plates exposed in latitude 35° N. in the course of three and a half years. The spectrographic evidence, then, is clear that there is a permanent aurora contributing towards the light of the night sky.

Rayleigh, working with a lens of great light-gathering power and with a small dispersion, has found in the spectrum of the night sky, in addition to the principal auroral line, two faint lines or bands of unknown origin at approximately $\lambda\lambda 4210, 4435$.|| These bands are probably to be connected with the aurora rather than with the light which comes from the meteoric or cosmical dust in the solar system which we see in the plane of the earth's orbit as the Zodiacal light. Present evidence points to this dust shining merely by reflected light from the sun.

* Vegard, *Phys. Zeit.*, xiv. 680, 1913.

† H. D. Babcock, *Ap. J.*, lvii. 218, 1923. McLennan and Shrum have identified a sharp line at this wave-length in a mixture of oxygen and helium (*Nature*, cxv. 382, 1925).

‡ *Proc. R.S.*, c. A, 367, 1921, and ci. A, 114, 1922.

§ *Phil. Mag.*, xlvi. 193, 1923.

|| *Proc. R.S.*, ciii. A, 45, 1923.

30. Comets.—The expulsion of matter from the sun suggested by the phenomena of auroræ and of magnetic storms brings to mind at once the tails of comets where we have visible evidence of matter in motion away from the sun. A comet consists essentially of a hazy cloud or head of faintly shining matter which usually contracts as the comet approaches the sun. As the head contracts, one or more bright nuclei generally form near its centre and a luminous tail of extreme tenuity streams out from the head in the direction away from the sun. The tail may be accompanied by envelopes on the same side of the comet's head as the sun, and in some cases * the comet may develop a whole series of envelopes as its nucleus passes through stages of alternating activity and quiescence (Plate 18). From the shape of the tail it is possible to calculate the ratio of the gravitational attraction to the repulsive force from the sun. Schwarzschild † and Nicholson ‡ have shown that if the tail consists of particles whose linear dimensions are of the same order as the mean wave-length of the incident light, then the pressure of solar radiation is competent to produce tails of the shapes observed. On the other hand, the velocity of matter in the tails of comets has been determined from the motion of nuclei in individual tails; these give much larger velocities than those suggested by the shapes of the tails and indicate repulsive forces of a higher order than could be given by radiation pressure: still more violent repulsions are required if the envelopes which form between the head of a comet and the sun are formed of matter expelled from the head towards the sun and driven back by the solar repulsion. The forms of the envelopes and the motions of individual nuclei in the tails present real diffi-

* Notably Comet Morehouse (1908c), *M.N.R.A.S.*, lxi. 52, 1908.

† *Sitz. d. Math. Phys. Classe zu München*, 1901-2, 193.

‡ *M.N.R.A.S.*, lxx. 544, 1910.



COMET MOREHOUSE, 1908c

Photographed with the 30-inch Reflector at the Royal Observatory, Greenwich, 1908,
October 30, 6 h. 37 m. G.M.T.

culties in the way of accepting the pressure of solar radiation as the sole factor in the repulsion of the matter which forms the tail, though it may well be one of the chief factors present.

It is permissible to suppose that the very tenuous gas shining in a comet's tail is illuminated by the passage of charged particles issuing either from the head of the comet or from the sun. The spectroscope shows that part of the light is reflected sunlight but that bright bands are superimposed, indicating the emission of light from the comet itself. Donati first noted these bands in 1864,* and Huggins † identified three bands in the spectrum of the head of Comet II, 1868, with three bands which he had found in examining the spectrum of certain compounds of carbon. These bands, with heads at $\lambda\lambda 5635, 5165, 4737$, form part of the "Swan" spectrum ‡ for the hydrocarbons, acetylene and methylene. Other bands of the "Swan" spectrum found in the heads of comets are at $\lambda\lambda 4365, 4371, 4382, 4685, 4698, 4715$. The presence of nitrogen in the head of a comet was indicated later by the cyanogen band at $\lambda 3883$, and the negative band at $\lambda 3914$; sodium was identified by bright [D] lines, and iron also by some of the Fraunhofer lines which appeared bright in the spectrum of the nucleus of the great comet of 1882.§ Sodium has been found in the nucleus of other comets, notably the daylight comet, 1910a, and Comet Wells, 1882a. The metallic lines are strengthened and the carbon bands weakened when the comet is close to the sun. The spectrum of the *head* of Comet Wells contained a series of unknown bright bands at $\lambda\lambda 4253, 4412, 4507, 4634, 4769$.|| and did not contain the ordinary

* *M.N.R.A.S.*, xxv. 114, 1864.

† *Phil. Trans.*, clviii. 529, 1868.

‡ *Transactions of the Royal Society of Edinburgh*, xxi. 411, 1856.

§ *Copernicus*, ii. 237, 1882.

|| Huggins, *Proc. R.S.*, xxxiv. 148, 1882.

hydrocarbon or cyanogen bands. The head of Comet Brooks, 1911c, also contained some unknown bands at $\lambda\lambda 3985, 4000, 4024, 4050, 4073, 4102, 4138$. Another series of bands which were observed at $\lambda\lambda 4002-22, 4255-75, 4548-70, 4690-4715$ in the tails of Comet Daniel, 1907d, and of Comet Morehouse, 1908c, have been traced by Fowler * to carbon monoxide. The tails consisted mostly of carbon monoxide, though cyanogen was possibly also present; sodium found strong in the nucleus was identified in the envelope, and possibly in the tail close up to the head.† It is of some interest that Merton has found these carbon-monoxide bands in helium vacuum tubes when only a small trace of carbon is present as an impurity.‡

31. Meteors.—The nature of the gas in a comet's tail is known. The source of this gas is less certain. It may be gas that has been occluded by the solid particles or lumps, which form the head, during the passage of the comet in the outer regions of the solar system or in some primitive heated condition. If a comet, after disintegration, crosses the earth's atmosphere, a shower of meteors is observed, believed to be due to collision of the earth with some of the remains of the comet. It is, perhaps, significant that the meteorites which have fallen to earth are generally full of occluded hydrogen, helium, and carbonic oxides. The spectrum of a meteor has been occasionally observed. The Balmer series of hydrogen lines were found by E. C. Pickering§ and the sodium line by v. Konkoly.|| Both of these are probably due to the atmosphere. The spectra of many meteoritic bodies have been determined. For the most part the bodies are composed of iron, nickel, cobalt, and chromium, but magnesium, sodium, calcium, silicon, among common ele-

* *M.N.R.A.S.*, lxx. 176, 484, 1910.

† Newall, *M.N.R.A.S.*, lxx. 460, 1910.

‡ *Phil. Trans.*, ccxxii. 386, 1922.

§ *Ap. J.*, vi. 461, 1897.

|| *M.N.R.A.S.*, xxxiv. 82, 1873.

ments, and gallium and rubidium, among rare terrestrial elements, have also been found.*

32. Planetary Bodies.—The applications of the spectroscopic to the chief bodies of the solar system are not numerous. Modifications of the solar spectrum by extra absorption bands, not yet identified, should, in time, throw light on the constitution of the atmosphere of Jupiter, Saturn, Uranus, and Neptune. In the case of Mars there has been a lively dispute, mainly between two schools of American astronomers, on the question whether deviations of the spectrum from the solar spectrum prove the presence of water-vapour in the Martian atmosphere. This dispute is not yet settled, and further work is required to decide whether the spectrum of Mars gives any indication of the presence of water-vapour in the Martian atmosphere. St. John and S. B. Nicholson have done preliminary work in the application of the powerful instruments of Mount Wilson to problems of planetary spectra. They have found that the spectrum of Venus gives no measurable evidence either of oxygen or of water-vapour in the atmosphere of Venus, though the investigation should have given positive results if in the double passage through the atmosphere of Venus to the surface (or to the effective reflecting layer) and back again the light had traversed the equivalent of 1 m. of oxygen or of 1 mm. of precipitable water-vapour.† The possibility of clouds high in the planetary atmosphere acting as the reflecting layer prevents this experiment from being finally decisive as to the atmosphere of Venus.

If Mars and Venus show little or no trace of atmospheric absorption in their spectra, the same cannot be said of the major planets. On the red side of $H\beta$ they all show striking differences from the solar spectrum, strong absorption

* See *Ap. J.*, vi. 221, 229, 1897; and *Spectroscopic Comparison of Metals*, South Kensington, 1907.

† *Ap. J.*, lvi. 380, 1922.

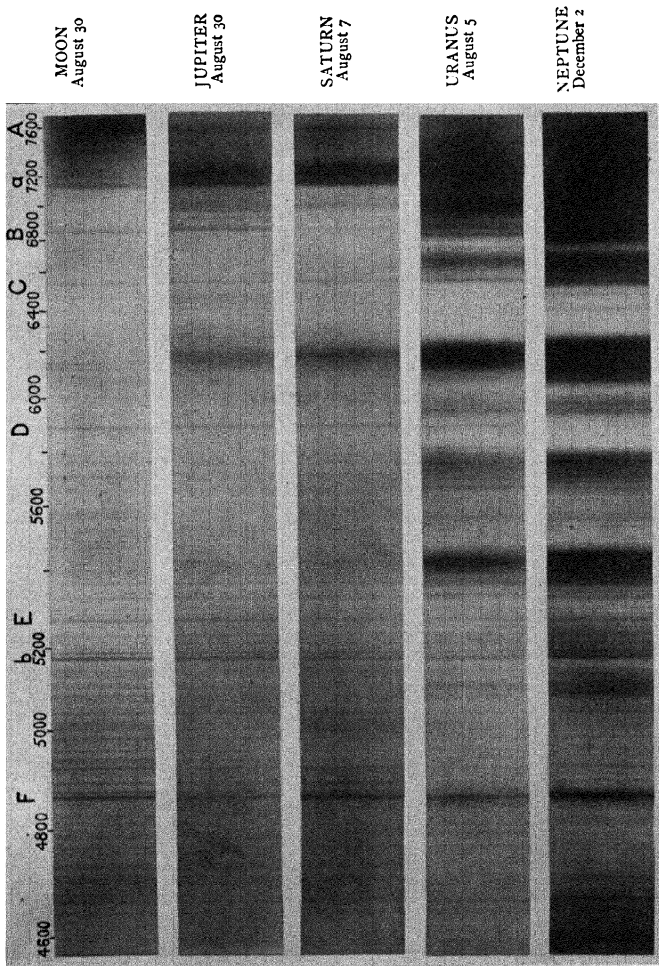
bands of unknown origin appearing in their spectra * (Plate 19). These unknown bands strengthen considerably and become more numerous for Uranus and still more for Neptune than for Jupiter and Saturn. The obvious suggestion that they are due to absorption by gases lying in interplanetary space is negatived by the fact that the rings of Saturn do not share the strong new bands shown in the spectrum of the ball. These new bands are presumably due to the sunlight having penetrated into the atmospheres of the planets before reflection. The hydrogen lines $H\alpha$ and $H\beta$ are both notably strengthened in Uranus and Neptune, but as $H\gamma$ and $H\delta$ are not similarly affected this may be due to coincidence with other bands. The principal unknown bands in the planetary spectra are at $\lambda\lambda 5093, 5428, 5762, 5973, 6191, 6677, 6812, 7022, 7195, 7260$. An identification of these with the absorption bands of chlorophyll has been suggested, but the evidence is not conclusive.

Keeler, † and later V. M. Slipher (Plate 20), applied the spectroscope to study the velocity of rotation of the planet Saturn and its rings, verifying the view of Maxwell as to the constitution of the rings and confirming the observed visual rate of rotation of the planet. This method has been applied to other planets whose rates of rotation could not be obtained by watching fixed markings rotate. Thus for Uranus, Lowell and V. M. Slipher found that the period of rotation of the planet was 10 h. 50 m., and that the axis of rotation was normal to the plane of the satellites. ‡ The equator is closely parallel to the plane containing the satellites and the rotation is in the same direction as that of the satellites, i.e. it is retrograde. The problem of the rotation period of Mercury, Venus, and Neptune has not yet been solved.

* V. M. Slipher, *Lowell Obs. Bull.*, No. 42, 1909.

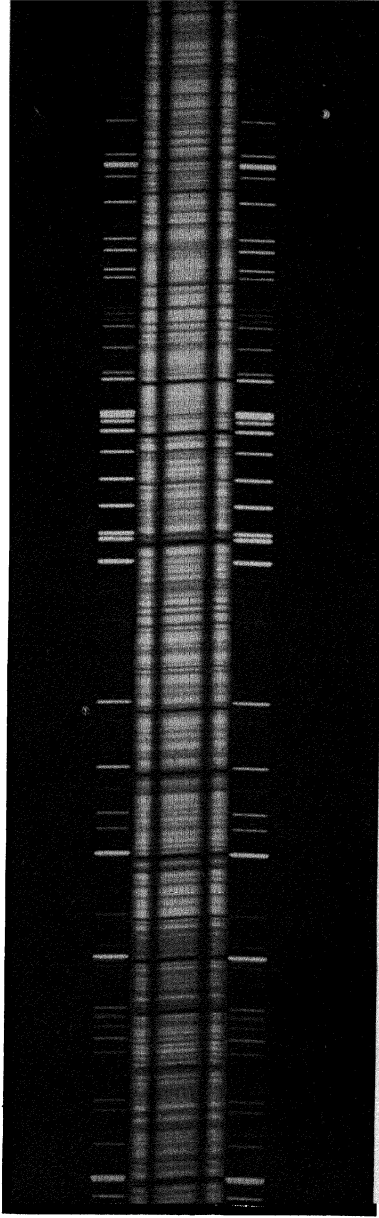
† *Ap. J.*, i. 416, 1895.

‡ *Lowell Obs. Bull.*, 53, 1912.



THE SPECTRA OF THE MAJOR PLANETS

Photographed, in 1907, by V. M. Slipher, at Lowell Observatory, Flagstaff, Arizona



42713 Fe

Vanadium Lines

41947 Fe

SPECTRUM OF SATURN

Photographed by V. M. Slipher at the Lowell Observatory. The slit was placed over the major axis of the ring system. The slant of the lines from the ball shows the axial rotation of Saturn and the reverse slant of the lines from the ring shows that the linear velocity is less for the outer edge of the ball than for the inner edge. The comparison spectrum is an iron and vanadium arc

In connection with the gaseous atmospheres, that the spectroscopist reveals on the major planets, there must be mentioned the high albedo or reflecting power for light incident on the planets. Russell * gives 0.59, 0.56, 0.63, 0.63, 0.73 as the visual albedos of Venus, Jupiter, Saturn, Uranus, and Neptune respectively, as compared with 0.073, 0.154 for the moon and Mars. The high albedo goes with reflection from cloud surfaces, the low values with reflection from rocks through little or no atmosphere. The albedo of the earth, 0.44, is intermediate between those of the cloudy and cloudless planets

The spectrum of Venus has been used by Evershed in the study of the relativity shift of the spectral lines. His idea was to study the integrated sunlight from a portion of the solar surface not facing the earth so as to eliminate in the determination of wave-lengths any earth-effect on the circulation in the solar atmosphere.

Lastly, we may mention the attempt to study the petrography of the moon's surface by photography through colour screens which only admit light from a narrow range of spectrum. R. W. Wood † and Miethe and Seegert ‡ have taken lunar photographs through different screens, noting the different colours of various portions of the moon's surface; on comparing his plates with photographs of various volcanic ejecta and igneous rocks, Wood suggested that sulphur is present in the dark spot near Aristarchus. Most of these applications of the spectroscopist and allied instruments to the solar system are incomplete, the astronomer's fancy having been captured by the larger problems awaiting investigation in the stellar universe. It may not be amiss to remind ourselves that there are problems nearer home still awaiting solution.

* *Ap. J.*, xliii. 173, 1916.

† *Ibid.*, xxxvi. 75, 1912.

‡ *A. N.*, clxxxviii. 9, 239, 371, 1911.

CHAPTER VI

STELLAR RADIATION

33. Stellar Magnitudes.—The *magnitude*, m , of a star is a measure of its *apparent* brightness. If a star's distance is known its apparent brightness may be transformed into its absolute brightness by reducing the observed brightness to the value that would be found if the star were a given fixed distance from the earth. The distance chosen for the measure of the *absolute* magnitude, M , of a star is 10 parsecs,* and the relation between M , m , and a star's parallax, π , (measured in seconds of arc) is $M = m + 5 + 5 \log_{10} \pi$.

The relation between a star's measured brightness, I , and its apparent magnitude, m , is given by the equation

$$-0.4(m - m_0) = \log_{10} I - \log_{10} I_0.$$

The zero for the scale is, of course, arbitrary. Here it will be sufficient to say that the limit of visibility for average unaided eyesight is magnitude 6.0, and that the sun's apparent magnitude at a distance of 149,600,000 kilometres has been estimated at $-26^m.72$, corresponding to an absolute magnitude of $4^m.85$.† The present normal scale was first given by Pogson, in 1854, after considerable work had been done by Dawes, Herschel, Johnson, and others, in securing a uniform scale of magnitude. Pogson's value

* A *parsec* is the distance at which the radius of the earth's orbit subtends an angle of 1 second of arc; it is approximately 308×10^{11} kilometres; 1 *parsec* = 3.26 light-years.

† *Ap. J.*, xliii. 105, 1916.

for the ratio of the amount of light from a star of any magnitude to that from a star of one magnitude fainter was 2.512.*

There is a fundamental difficulty in measuring accurately even the apparent brightness of a star. The light received by the observer may have been measured by an eye or by a photographic plate. The eye and the photographic plate are chiefly sensitive to different portions of the spectrum, and photographic plates prepared with different emulsions differ in their sensitiveness from one another. Again, the selective absorption of the atmosphere, the glass of the telescopic objective, or the silvered surface of the reflector adds a further complication in the determination of the stellar brightness. It is not to be wondered at that the different scales prepared at Göttingen, Greenwich, Harvard, Potsdam, the Cape, Mount Wilson, and Yerkes Observatories have to be reconciled to one another by corrections depending on the magnitudes, and on the colours of the stars. At the Rome meeting of the International Astronomical Union, 1922, Professor Seares presented the report of the Committee on Stellar Photometry,† giving for a number of stars near the North Pole the best recent determination of their photographic and photovisual magnitudes, and also of their colour-indices. The report also gives the corrections required to convert the magnitude scales determined at the different observatories to the standard scale adopted by the International Astronomical Union. [The colour-index of a star is the difference between its photographic and visual or photovisual ‡ magnitude ; colour-index = photographic

* *Radcliffe Observations*, xv. 16, 1856.

† *Trans. I.A.U.*, i. 69, 1922.

‡ The photovisual magnitude is the magnitude determined photographically on an isochromatic plate exposed behind a yellow filter giving results approximately agreeing with those obtained from eye-observations. The standard plate and filter for this purpose have not yet been fixed by international agreement.

magnitude minus visual or photovisual magnitude (see § 36 below).]

34. Black-Body Radiation and Effective Temperature.—

The problem of determining the temperature of the stars was first attacked by an application of the second law of thermodynamics. We cannot yet secure in the laboratory artificial sources of heat which are directly comparable with stellar photospheres. We must either reduce the stellar radiation by the intervention of suitable reflecting mirrors and absorbing media before making the comparison * with laboratory results, or we must extrapolate by the laws of radiation, from observations of bodies of lower temperature, to the observed distribution of the continuous radiation in the spectrum of the stars. The whole subject is complicated by questions such as the selective absorption of the light, coming in from the star by the earth's atmosphere and the optical train. There is further, an underlying assumption that the light analysed is purely a temperature radiation and obeys in its distribution the laws of thermodynamics for such radiation. This would be true if the star were a mass of gas at a uniform temperature, if there were no scattering of radiation, and if every part radiated as it would in a steady state. The presence of temperature gradients in the star, the difference of transparency of the outer layers for different parts of the spectrum, the absorption lines in the spectrum and gaseous scattering in the stellar atmosphere all tend to cause departures from the black-body spectrum. The fact remains that the star's continuous spectrum does approximate to that of a black body, and a study of its distribution does give a reasonable guide to the temperature of the star at the average depth from which the emerging radiation comes. This temperature, the black-body temperature most nearly corresponding in amount and composition to the radiation emerging from the star, is called the effective temperature of the star.

* See Wilsing, *Potsdam Pub.*, No. 76, 1920.

All that need be said here as to the distribution of radiation from a black body at temperature T is that if E_λ is the intensity of radiation corresponding to wave-length λ , $E_\lambda = \frac{F(\lambda T)}{\lambda^5}$, where the function F has a form determined by experiment. The wave-length λ_m for which E_λ is a maximum, is related to T by the relation $\lambda_m T = \text{constant}$, i.e. as T increases the wave-length of maximum radiation moves towards shorter wave-lengths. Also the maximum intensity E_{λ_m} varies as T^5 .

35. Stellar Temperatures.—We pass to the application of these results to stellar problems. The first study of the energy distribution in stellar spectra was a comparison of the relative brightness of a star's spectrum at a number of selected wave-lengths clear of strong absorption lines.

Planck's formula of radiation— $E_\lambda \propto \lambda^{-5} \left(e^{\frac{c}{\lambda T}} - 1 \right)^{-1}$, where c is the velocity of light—was used to determine the value of T that most clearly fitted the observations of any particular star. The early work of Wilsing, Scheiner, and Münch at Potsdam was visual,* as also was that of Nordmann,† who used a number of coloured screens in his heterochrome photometer. Rosenberg ‡ made a photographic study of the same problem by a method which also involved a comparison of the density of a spectrogram at a number of different parts of the spectrum. Coblenz,§ using a vacuum thermo-couple and a series of transmission screens, has also studied the energy distribution in stellar spectra and derived a temperature scale for the stars. H. H. Plaskett,|| by the

* *Potsdam Pub.*, xix. No. 56, 1909; xxiv. No. 74, 1919.

† *C.R.*, cxlix. 557, 1038, 1909; clxxiii. 72, 1921; *Bull. Ast.*, xxvi. 9, 167, 1909.

‡ *Abh. d. K. Leop-Karol Deutschen Akad. der Naturforschen zu Halle*, ci. 65, 1914.

§ *Proc. N.A.S.*, viii. 49, 1922.

|| *Pub. D.A.O.*, ii. 213, 1923.

use of a neutral tint wedge, placed in front of the spectro-scope slit, has studied the distribution of intensity along the whole range of the photographed spectra of stars, and Jules Baillaud * has also studied the distribution of energy by comparing the stellar spectrum with a series of strips of graduated density taken on the same plates as the stellar spectrum, with which they are compared.

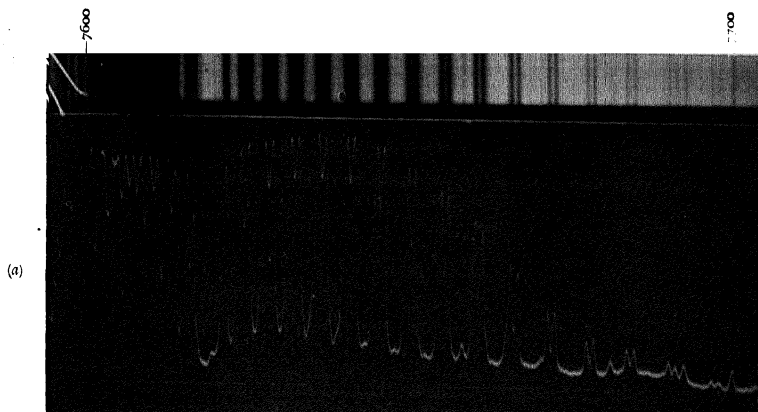
Sampson has published † a preliminary study of stellar temperatures based on the measurement of the density of stellar spectrograms along the whole range of the photographed spectra. His method is to pass a spectrogram across the slit of a photometer and to record the effect of a standard beam of light passing through the spectrogram and falling on a photo-electric cell (Plate 21). This investigation gives the most sensitive results so far obtained for a detailed study of the continuous spectrum of a star. There are photographic and other instrumental difficulties to be met, but the method makes it easy to deal with the whole range of the spectrum with an accuracy and sensitiveness far beyond that of the human eye, and it is likely to become the standard method of stellar spectro-photometry.

For the hottest stars higher temperatures than those deduced by Wilsing, Coblentz, and Sampson have been indicated by another attack on the problem of stellar temperatures initiated by Saha.‡ The fundamental ideas of Saha's theory are: (1) that in stellar atmospheres the ionization of a gas—the dissociation of its atoms into positively charged ions by the loss of one or more electrons—depends upon its temperature, its pressure and the nature of the gas and of the other gases with which it is mixed; (2) that the presence or absence of certain series of lines in the stellar spectrum indicates the condition of ionization of the gas concerned—

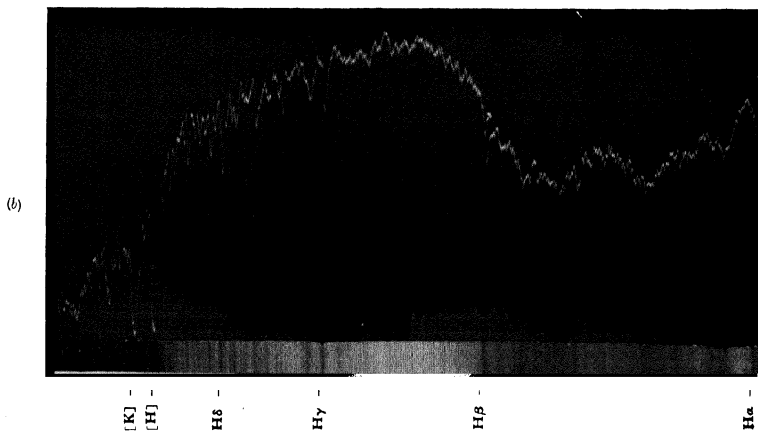
* *Ann. de l'Obs. de Paris*, xxx. 1914. *C.R.*, clxxvii. 424, 1924.

† *M.N.R.A.S.*, lxxxiii. 174, 1923; xxxv. 212, 1925.

‡ For references see § 14 above.



(a) SOLAR SPECTRUM, REGION INCLUDING FRAUNHOFER'S [A] LINE



(b) POLARIS, F8, SPECTRUM OBTAINED WITH AN OBJECTIVE PRISM AND A 6-INCH PHOTOVISUAL LENS

Spectrophotograms taken by R. A. Sampson at the Royal Observatory, Edinburgh

some lines only appearing when a sufficiently large proportion of the atoms are ionized (by the loss of one, two, or three electrons) and some lines disappearing only when practically all the atoms of the element are ionized. An examination of the spectra of different elements in a stellar spectrum leads to a knowledge of the condition of ionization of the corresponding gases in the absorbing layer of the star. With certain assumptions as to the pressure of the gas, theory enables us to deduce its temperature. Saha assumed that the mean partial vapour pressure of an element in that layer of a stellar atmosphere, which contributed to certain absorption lines, lay between 1.0 and 0.1 of an atmosphere. This value of the pressure is now known to be too high, and the resulting temperature scale for the various spectral types derived by Saha has, consequently, to be modified.

R. H. Fowler and Milne,* arguing from the difficulty of deciding the reasons for the marginal appearance or disappearance of a line, have modified the applications of Saha's theory to stellar temperatures by determining the conditions which govern the appearance of given absorption lines at maximum intensity. Assuming that the maximum concentration of atoms suitably excited coincides with the maximum intensity of the corresponding lines this maximum concentration is theoretically connected with the ionization, pressure, and temperature of the stellar atmospheres. Comparing the evidence from different elements with the known probable temperatures of the stars where certain lines are strongest, they have obtained strong converging evidence that the pressures concerned are of the order of 10^{-4} atmosphere. The resulting scale of temperatures covers a wider range than the original scale of Saha. The determination of the highest temperatures is complicated

* *M.N.R.A.S.*, lxxxiii. 403, 1923 ; lxxxiv. 499, 1924.

by the presence of bright lines in the spectra and cannot yet be considered as settled.

The following table gives the conclusions as to stellar temperatures derived by the afore-mentioned methods.

TABLE II
STELLAR TEMPERATURES

Spectral Type.	Wilsing.	Nordmann.	Rosenberg.	Coblentz.	Sampson.	Plaskett.	Saha.	R. H. Fowler and Milne.
O5	—	—	—	—	—	—	(Oa)23,000	>35,000
B0	12,300	—	30,000	13,500	25,000	15,000	18,000	26,500
B1	—	27,700	—	—	—	—	—	19,000
B2	—	22,000	—	—	20,000	—	—	16,500
B5	11,450	—	18,000	—	—	—	14,000	—
A0	10,250	—	12,000	9,500	13,100	—	12,000	10,000
A5	9,000	14,000	9,000	8,000	10,700	9,000	—	—
F0	7,950	—	7,850	—	8,900	—	9,000	7,500
F5	6,880	7,000	6,930	6,500	7,400	—	—	—
G0	5,980	—	6,000	6,000	6,200	6,000 to 5,500	7,000	6,000
G5	5,250	—	5,200	—	5,100	—	—	5,300
K0	4,570	5,000	4,570	—	4,200	5,500 to 5,000	—	4,500
K5	4,000	3,600	3,840	—	3,500	—	—	3,900
M0	3,550	3,100	3,580	3,300	3,400	—	5,000	3,000

The values originally obtained by Wilsing and his colleagues were modified in subsequent investigations. For his work and that of Rosenberg, the tables derived by Brill * from a comparative study of their data have been used.

36. Colour-Index.—Closely connected with the determination of the wave-length of maximum radiation of a star is the question of its colour-index. Owing to the difference in colour-sensitiveness between the eye and the ordinary photographic plate, different scales of magnitude have been found for stars of different types. The colour-index of a star is the difference, photographic magnitude minus visual or photovisual magnitude. The purely visual magnitudes dependent on the colour perception of an individual observer are being replaced by photovisual magnitudes depending on photography through a suitable yellow filter on to isochromatic plates. But, even so, the optical conditions for determining a standard photovisual scale have not been decided. Both in photographic and in photovisual work, each instrument introduces its own disturbing factor. A scale for photographic work down to magnitude 20 has been adopted by the International Astronomical Union, and a list of magnitudes of stars near the North Pole has been published by the same body.† This is available for all observers and instruments in the northern hemisphere. A final photovisual scale has not yet been adopted, though one has been given by Seares at Mount Wilson which is not likely to have systematic errors of more than a few hundredths of a magnitude. The colour-index is naturally a function of the star's spectrum. The exact connection between the two will depend on the standard scale adopted. Though no final table is yet available, the general run is well shown in the figures used in the Harvard catalogue ‡

* *A.N.*, cccix. 356, 365, 1923. † *Trans. I.A.U.*, i. 69, 1922.

‡ *Harvard Annals*, lxxx. 151, 1917.

and derived from investigations at Harvard, the Cape, Göttingen, and Yerkes. The colour indices of the classes Bo, Ao, Fo, Go, Ko, and M, are given as $-0.24, 0.00 + 0.28 + 0.56 + 1.00$, and $+1.35$ respectively. This scale should really only be applied to dwarf stars. Giant stars, especially for types Go to K5, are redder than dwarf stars of the same type and have colour-indices that are greater than the above scale by as much as 0.5.*

The above scale of colour-indices corresponds to two standard mean wave-lengths, λ_{v_0} , λ_{p_0} , used in comparing two given sets of photovisual and photographic magnitudes. The adjustment to 0.00 for Ao dwarfs and 1.00 for Ko dwarfs is conventional, and applies to these two standard wave-lengths. The reduction of any other set of colour-indices to this scale is equivalent to a change from the λ_v , λ_p used in this other investigation to the standard values λ_{v_0} , λ_{p_0} , to which the standard scale refers.

37. Effective Wave-Length.—A quantity which has been used along with the colour-index as a simple substitute for accurate spectrophotometry in the case of the fainter stars is the effective wave-length.† This is the wave-length obtained from the separation of successive images of the star when a coarse grating is placed over the objective of the telescope (see § 10 (a) above). As with the colour-index, there is naturally a close correlation between the spectral type and the effective wave-length of a star. The effective wave-lengths are dependent on observational and instrumental conditions, and no definite standard scale has yet been adopted, but Davidson and Martin ‡ have given the following table connecting effective wave-lengths and spectral types. For convenience of reference the Harvard

* Seares, *Pub. A.S.P.*, xxxiv. 56, 1922.

† See Bergstrand, *Nova Acta R. Soc. Scient. Upsaliensis* (ser. IV), ii. No. 4, 1909; and Hertzsprung, *Potsdam Pub.*, xxii. No. 63, 1911.

‡ *M.N.R.A.S.*, lxxxiv. 430, 1924.

colour-index and R. H. Fowler and Milne's temperatures are repeated in the same table.

TABLE III

EFFECTIVE WAVE-LENGTH AND COLOUR-INDEX

Spectral Type.	Effective Wave-length.	Colour-Index.	Temperature.
B ₀	4105	— 0.24	26,500° K.
B ₅	4186	— 0.12	—
A ₀	4250	0.00	10,000
A ₅	4270	+ 0.14	—
F ₀	4278	+ 0.28	7,500
F ₅	4292	+ 0.42	—
G ₀	4320	+ 0.56	6,000
G ₅	4396	+ 0.78	5,300
K ₀	4474	+ 1.00	4,500
K ₅	4540	+ 1.18	3,900
M ₀	4580	+ 1.35	3,000

38. Stellar Diameters.—An interesting application of the black-body theory of stellar radiation was made by Hertzsprung.* From the knowledge of a star's effective temperature a value for the surface intensity of the outgoing radiation can be derived. The radiation received by the observer from the star is equal to the surface intensity multiplied by the solid angle subtended at the observer. The radiation received is measured by the star's apparent magnitude, the sun, a star of known angular diameter and of known surface intensity, providing the constant necessary to complete the equation. Observation of a star's apparent magnitude and of its temperature are sufficient, then, to give a determination of the solid angle it subtends or, more simply, of its angular diameter. Nordmann,†

* *Zeitschrift für wissenschaftliche Photographie*, iv. 43, 1906.

† *C.R.*, clii. 73, 1911.

Wilsing,* Eddington,† Russell,‡ and Bottlinger § have, in this way, formed estimates of the angular diameters of certain stars. The simplest formula used is the one adopted by Hertzsprung who has calculated the angular semi-diameter, ρ , for 734 stars. || If T° is the absolute temperature of a star, and m its visual magnitude then

$$5 \log \sin \rho = -43.44 + 2.3 \left(\frac{14600}{T} \right)^{0.93} - m.$$

At the date when the earliest estimates were made, no actual measures of stellar diameters were available. But in December, 1920, measures made with the 20-foot Michelson stellar interferometer, mounted on the 100-inch Hooker telescope at Mount Wilson, confirmed very closely the theoretical value for the angular diameter of α *Orionis*. Eddington had given 0.051 for the angular diameter of this star, the measured value of Michelson and Pease was 0.047. ¶ Subsequently the diameters of α *Bootis* and α *Scorpii* were measured and found to be 0.022 and 0.040, Eddington's estimate for them being 0.020, 0.043 respectively. With the best available values for the parallaxes of the three stars, α *Bootis*, α *Orionis*, and α *Scorpii*, their diameters have the respective values 34,000,000 km., 344,000,000 km., and 640,000,000 km. respectively, as compared with 1,390,000 km. for the sun.** The last-named star, Antares, if placed at the sun's centre, would extend not only beyond the earth's orbit but well beyond the orbit of Mars.

* *Potsdam Pub.*, xxiv. No. 76, 1920.

† *British Association Report*, 1920, 42.

‡ *Popular Astronomy*, xxix. 31, 1921.

§ *Veroff. d. Universitätssternwarte zu Berlin-Babelsberg*, iii. No. 4, 1923.

|| *Annalen van de Sterrewacht te Leiden*, xiv. 20, 1922.

¶ *Ap. J.*, liii. 249, 1921.

** Hale, "The New Heavens," 57, 1922.

The existence of giant stars, much more luminous than the sun, was thus confirmed by direct measurement some fifteen years after Hertzsprung had first divided stars into two groups of high and low luminosity. The mean density of Antares is probably of the order of $10^{-8} \times$ the mean density of the sun, an unexpectedly low figure in view of its banded spectrum and of the slight ionization shown by the other lines in its spectrum. An indication that the diameter of *α Orionis* is varying along with its brightness and its radial velocity * suggests that there may be important applications of the stellar interferometer to be made to add to the understanding of the theory of stellar variation.

39. Stellar Masses.—The study of radiation has led to conclusions, verified by other investigations, on stellar temperatures and diameters. It remains to note how radiation enters into the question of stellar masses. Eddington, in a series of papers,† has discussed the part that the pressure of radiation plays in the equilibrium of a star.

With certain assumptions as to the high stage of ionization found in the interior of a star he found a simple relation connecting the mass, the absolute magnitude of a star and the coefficient of reduction of the constant of gravitation, β (when radiative pressure is taken into account in the pressure equation we replace G , the constant of gravitation, by βG).

The first striking result obtained by Eddington was that, within a small range of values for stellar masses (the range including the sun's mass), radiation pressure increased with increasing mass from a small fraction of gravitation to four-fifths of gravitation; at the same time the absolute magnitude brightened from that of extremely faint stars to that of the brightest known stars. When radiation

* *Pub. A.S.P.*, xxxiv. 346, 1922.

† *M.N.R.A.S.*, lxxvii. 16, 596, 1917; lxxxiii. 32, 98, 1922; *Ap. J.*, xlvi. 205, 1918.

pressure approaches gravitation in value the equilibrium of a star is much more liable to break down through such causes of instability as rotation, and thus stars many times the sun's mass would be likely to break up into smaller masses.* On the other hand, stars much less massive than the sun would not be bright enough to be seen. Radiation pressure thus supplied a good reason why the visible stars should lie within a narrow range in mass, a state of affairs recognised from data as to binary stars, but first explained in terms of radiation. An extract from Eddington's table † gives his estimate for a star in radiative equilibrium of effective temperature 5200° K. (The absolute magnitude requires a small additional term $-2 \log_{10} (T_e/5200)$ for stars of effective temperature T_e° .)

TABLE IV
MASS AND ABSOLUTE MAGNITUDE

Mass ($\odot = 1$).	Absolute Magnitude.	$1 - \beta$.
0.1284	+ 14.143	0.001
0.2233	+ 11.513	0.003
0.4135	+ 8.615	0.010
1.004	+ 4.645	00.5
2.050	+ 1.884	0.14
3.774	- 0.052	0.26
7.117	- 1.718	0.40
19.62	- 3.919	0.60
37.67	- 5.162	0.70
90.63	- 6.714	0.80

Comparing the theoretical curve connecting mass and absolute magnitude with known values for individual stars,

* The most massive star so far discovered is ν *Sagittarii*, a binary whose components together are more than 300 times the mass of the sun (Ludendorff, *Sitz. Preuss. Akad. d. Wiss.*, 1924, p. 67).

† *M.N.R.A.S.*, lxxxiv. 310, 1924.

Eddington found remarkably close agreement of observation and theory not only for the very luminous massive stars, but also for the fainter stars of small mass. These latter stars had not previously been suspected of obeying the gas laws: the explanation offered by Eddington is that the high state of ionization holding within a star and the consequent stripping of atomic nuclei of their outer rings of electrons mean that it is still possible for the gas-laws to be obeyed, even for the high densities which prevail in the faint stars of small mass. Another unexpected result of Eddington's investigation, in addition to the explanation of the narrow range of stellar masses and the obedience of dense stars to the gas-laws, is the high value given for the opacity of stars. The stars are amazingly opaque to radiation. The value for the opacity given by Eddington * for Capella is 150 in C.G.S. units; the opacity is nearly constant throughout the star, and if we measured it at that layer of Capella where the density is that of the terrestrial atmosphere, we should get the surprising result that four-fifths of the radiation was absorbed in passing through a layer 15 cm. thick.

* *Nature*, cxi., supplement to 12th May, 1923, p. x.

CHAPTER VII

MOTION IN THE LINE OF SIGHT

40. Doppler's Principle.—Doppler * was the first to perceive that the wave theory of light involved a change in the observed wave-length of light from a given source, corresponding to motion of the source relative to the observer. The application that he made of this idea to explain the colour of stars was false in that the light from a star extends on both sides of the visible range of the spectrum, and changes due to the motion of a star in the line of sight would take place simultaneously at both ends of the spectrum. The slight shift in the position of maximum intensity would lead to no appreciable colour change for ordinary stellar velocities. It was Fizeau who, in 1848, lecturing to the Société Philomathique de Paris, pointed out that Doppler's principle could be applied to the position of a line in the spectrum, and that the motion of a source relative to the observer could be measured by the displacement of a spectral line from its normal position.

Let c = the velocity of light, the same in all directions

(2.9982×10^{10} cm./sec. *in vacuo*).†

n, λ = the frequency and wave-length of a light-vibration emitted by a moving source and assumed to be independent of the motion of the source.

n', λ' = the observed frequency and wave-length of the vibration.

* *Abh. d. K. Böhmischen Gesell. d. Wiss.*, ii, 467, 1842.

† *Ap. J.*, lx, 256, 1924.

u = the relative velocity of the source and the observer resolved along the line of sight and measured positively when the source recedes from the observer.

Then consideration of the number of waves that reach the observer in a given time shows that

$$\frac{n'}{n} = \frac{c - u}{c}.$$

If $\delta\lambda$ = the displacement of the line in the spectrum towards the red, we have, for the case where u is small compared with c ,

$$\frac{\delta\lambda}{\lambda} = \frac{\lambda' - \lambda}{\lambda} = \frac{n - n'}{n'},$$

since by definition

$$n'\lambda' = n\lambda = \frac{u}{c}.$$

For a source receding at velocity u from the observer, we have an increase in the observed wave-length of $u\lambda/c$ for a line of undisplaced wave-length λ . It has been a common practice to speak of $c\delta\lambda/\lambda$ as the velocity in the line of sight or the radial velocity of a star; this is taken to be positive when $\delta\lambda$ is positive, i.e. when the source is receding from the observer. For certain investigations, notably on novæ, the custom has been recently introduced of discussing certain displacements, varying directly with λ , in terms of a *displacement factor* $10^4\delta\lambda/\lambda$, thus avoiding the issue as to whether the displacements are, or are not, due to velocity in the line of sight. (The velocity in km./sec. is obtained from the displacement factor by multiplying the latter by 30.)

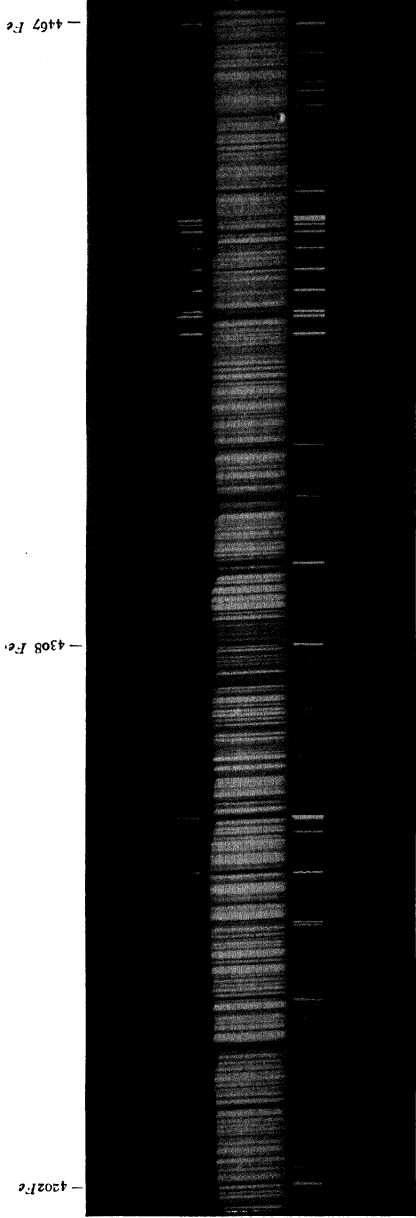
41. Radial Velocity.—Fizeau mentioned in his original paper how a study of line of sight velocities for the components of certain visual binaries would enable us to determine their parallaxes and, Mach, a few years later,* pointed

* *Sitzungsb. d. K. Akad in Wien*, xli. 543, 1860.

out how the principle could be applied to distinguish between lines of solar and telluric origin in the solar spectrum. The general application to stellar velocities depends essentially on our correct identification of the lines of absorption or emission to be used in comparing the stellar spectrum with known terrestrial sources of light. There is no difficulty in this for stars, whose spectra are of well-determined types, and consistent results for different elements represented in the same stellar spectrum are now easily obtained. The early visual observations, with the exception of Keeler's * at the Lick Observatory, in 1890, proved unreliable. Vogel and Scheiner, at Potsdam, and Belopolsky, at Pulkovo, were amongst the pioneers in photographic determinations, their work dating from about 1890. It was at the Lick Observatory again, that greatly increased accuracy in the determinations of radial velocities by photographic methods was obtained in the hands of Professor Campbell. Working with the 36-inch telescope and the Mills spectrograph, he reduced the probable errors of radial velocities to one-fifth of their previous value and greatly diminished the prevalent systematic errors. His probable error was given at 0.5 to 0.25 km./sec., and this accuracy led at once to an enormous increase in the number of known spectroscopic binaries. At the present time the claim of the Lick Observatory to lead in all radial velocity work is being challenged by the Dominion Astrophysical Observatory at Victoria B.C. (where J. S. Plaskett, with the aid of a 72-inch reflector, is rapidly adding to our knowledge of the radial velocities of stars) and also by the Mount Wilson Observatory, where Adams has been carrying out a heavy programme of work with the 60-inch reflector.

42. Applications to the Planets.—The applications of the Doppler effect within the solar system are interesting.

* *Pub. Lick Obs.*, iii. 195, 1894.



SPECTRUM OF JUPITER

Photographed by V. M. Slipher at the Lowell Observatory. Slant of lines measures rate of rotation of planet. Comparison spectrum Fe and V

First, we may mention Keeler's observation of the rings of Saturn,* whereby he verified Clark Maxwell's theory of the nature of the rings. He placed the slit across the planet in the plane of the ring; the lines in the spectrogram corresponding to the ball came out inclined to the lines of the comparison spectrum, the natural result of the rotation of the planet; but the lines corresponding to the ansae of the rings had an opposite slope (Plate 20) to that of the lines due to the ball. This naturally follows from the fact that as you pass out along a radius of the planet's equator, the velocity in the line of sight due to the rotation steadily increases, but as you pass out along the plane of the ring, the velocity due to the orbital motion of the particles forming the ring decreases again. The known velocity of rotation of the principal planets with constant or nearly constant markings act as a check on the velocities found from the slope of the spectral lines and encourage confidence in the method when applied to planets of indefinite markings (Plate 22). V. M. Slipher,† at the Lowell Observatory, has, in this way, determined the period of rotation of Uranus as being 10 h. 50 m., the direction being retrograde or in the same sense as that of the revolution of its satellites. The period of rotation of Venus is still uncertain.

43. Solar Rotation.—As mentioned already, Mach saw the value of Doppler's principle as a means of sorting out, in the solar spectrum, lines of true solar origin (which would show relative shifts when photographed from the west and east limbs) from lines of telluric origin arising from absorption in our atmosphere. A measure of the shift in different solar latitudes leads, of course, to a determination of the sun's rotation. In this way the law of rotation was extended to the polar regions from the lower latitudes, to which previous determinations, obtained from the observed

* *Ap. J.*, i. 416, 1895.

† *Lowell Obs. Bull.*, No. 53, 1912.

motions of sunspots, had been limited. The newer determinations are unaffected by variations in the drifts of the spots, but they are, of course, affected by local currents and by some uncertainty as to the depths of the layers involved in producing the lines whose shifts are being measured.* As Adams showed,† the rotational velocity of gases at the higher level corresponding to the hydrogen line $H\alpha$ is larger than for the lower level of the reversing layer. Also the equatorial acceleration found for sunspots and the reversing layer vanishes for the upper layers. The meaning and results of these differences have not yet been worked out in terms of the general problem of the circulation of the solar atmosphere. Other questions remaining unsolved in regard to the solar rotation are the variability of the rate of rotation apart from temporary and local fluctuations and also differences of behaviour between the northern and southern hemispheres of the sun.

44. Reduction to Sun.—Before returning to the application of Doppler's principle to stellar investigations, it is as well to give a brief account of the corrections that have to be made to the observed radial velocity to allow for the motion of the observer. We have to take into account (*a*) the motion of the earth round the sun; (*b*) the motion of the observer about the earth's axis; and (*c*) the motion of the earth round the centre of inertia of the earth-moon system. There is a further term allowing for the motion of the sun round the centre of inertia of the solar system. This amounts at most to 0.015 km./sec., of which about four-fifths comes from the Jupiter term. It can, in general, be ignored. The values of the corrections (*a*), (*b*), and (*c*) are given below.‡ The corrections are given with the right sign for *addition* to the observed radial velocity of the

* See § 26 above.

† *Aph. J.*, xxvii. 217, 1908.

‡ I follow the treatment of Schlesinger, *Aph. J.*, ix. 159; x. 1, 1899.

star, radial velocity being reckoned positive when away from the observer.

(a) Correction for annual orbital motion—

Let λ, β = longitude and latitude of the observed star
(taken in practice to the nearest minute).

\odot = sun's longitude at the time of observation
(mid-exposure).

Π = longitude of sun at perigee
= $281^{\circ} 39' + 1.03' (t' - 1925.0)$, where t'
is the date of the observation.

a = semi-major axis of earth's orbit (149,600,000
km.).

e = eccentricity of earth's orbit (0.0168).

T = length of sidereal year in seconds (31,558,150).

v = mean velocity of earth in its orbit.

$$= \frac{2\pi a}{T(1 - e^2)^{\frac{1}{2}}} = 29.77 \text{ km./sec.}$$

Then the correction to the observed velocity of recession is

$$V_a = v \cos \beta \{ \sin (\odot - \lambda) + e \sin (\Pi - \lambda) \}$$

We put $b = v \cos \beta$.

$$c = v \cos \beta \cdot e \sin (\Pi - \lambda) ;$$

b and c can be determined once for all for a given body and are independent of the epoch—save for small secular corrections.

Then $V_a = b \sin (\odot - \lambda) + c$.

(b) Correction for daily motion—

Let A = earth's equatorial semi-diameter.

τ = length of sidereal day in mean seconds
(86164.1).

ϕ = latitude of observer.

ρ = radius vector from earth's centre to observer.

δ = declination of star.

t = western hour angle of star.

then $V_b = -\frac{2\pi A}{\tau} \rho \cos \phi \sin t \cos \delta$.

For a particular observatory a table can be formed with t and δ as arguments. In general, t is taken as the time of mid-exposure of the plate. The maximum value of this correction at the equator is 0.47 km./sec.

(c) For the monthly term we have a similar expression to that for the annual term, but we can neglect the eccentricity of the lunar orbit and its inclination to the ecliptic.

Let ϱ = longitude of moon at time of observation.

Then $V_c = v_m \cos \beta \sin (\varrho - \lambda)$,

where $v_m = 0.0124$ km./sec., taking the mean distance of the moon as 60.27A, and the mass of the earth as 81.70 times the moon's mass.

The total correction to the observed velocity of the star to allow for the observer's velocity in the line of sight relative to the sun is $V_a + V_b + V_c$. For refined work it may be necessary to take into account the velocity of the sun relative to the centre of inertia of the solar system.

45. The Solar Motion.—Herschel, in 1783, first investigated * the motion of the solar system among the stars from the study of the thirteen proper motions of stars then known. He found that the sun was apparently moving towards λ *Herculis*. Since then many statistical studies of the sun's motion have been made. Kapteyn showed † that the hypothesis of random motion for the stars on which these determinations were mainly based was not well founded, and that the main body of the stars showed preferential motions in two directions. The two star-drifts can be represented as a passage of one group of stars through another, the solar motion being superimposed on them. From a study of the proper motions in Lewis Boss's "Preliminary General Catalogue," Eddington ‡ derived a position

* *Phil. Trans.*, lxxiii. 247, 1783.

† *British Association Report*, 1905, 257.

‡ See "Stellar Movements," Eddington, p. 102, 1914.

for the apex towards which the sun is moving as

$$\alpha = 267.2^{\circ}, \quad \delta = + 36.4^{\circ}.$$

Campbell's position * of the solar apex and value for the sun's velocity derived from the radial velocities of 1047 stars was

$$\alpha = 273.5^{\circ}, \quad \delta = + 28.0^{\circ}, \quad \text{and } V = 17.73 \text{ km./sec.}$$

This gives a further correction to the observed velocity of a star at a position (α, δ) as

$$V_s = + 17.73 \cos(\alpha - 273^{\circ}) \cos(\delta - 28^{\circ}) \text{ km./sec.}$$

The figures must remain for the present uncertain. There are several outstanding puzzles in connection with stellar velocities in general and the radial velocities fully share in these puzzles. There is evidence for the presence of at least two other groups of stars systematically drifting through space, in addition to the two principal streams discovered by Kapteyn. It is inevitable that the position of the solar apex should depend on the stars selected for use in its determination. This comes out, if we determine the solar motion from stars of different spectral types,† or from stars of different velocities in space. Thus Strömberg ‡ has shown that the solar velocity V , comes out at 20.6 km./sec. when determined from 1026 stars of types F to M of space-velocities lying between 0 and 60 km./sec.; but from a study of 210 stars of the same spectral types with space velocities between 60 and 100 km./sec., he has found that the solar velocity, V , comes out at 36.3 km./sec. And further, the value for the solar velocity increases rapidly as the velocities of the stars used to determine it also increase. This must mean that the fast-moving stars are streaming

* "Stellar Motions," Campbell, p. 189, 1913.

† Boss, *A. J.*, xxvi. 187, 1911.

‡ Strömberg, *Ap. J.*, lvi. 265, 1922.

systematically in a direction opposed to the sun's motion ; Oort * gives the apex for these fast stars at $\alpha=125^\circ$, $\delta=-44^\circ$.

46. Stellar Motions and Spectral Types.—Applying the correction for the sun's motion to the observed velocity of a star, we get the radial velocity of the star relative to the system of stars employed in the determination of the solar motion. A statistical study of a large number of stellar velocities brings us at once face to face with a number of problems. Thus we find that stars of early type, B₀ to B₉, show a marked excess of positive radial velocities over negative velocities. The mean value for 138 of these stars was found by Campbell to be + 4.93 km./sec.† It is improbable that the universe of B stars is expanding at this rate, and some other explanation of the mean positive radial velocity seems to be required. It has been partly traced to errors in the assumed laboratory wave-lengths of the stellar lines used in determining the radial velocities,‡ but the complete explanation can hardly come in this way. For Gerasimovič has shown § that this outstanding mean velocity term, the so-called K-term, varies in value with the star's mass, while Freundlich and v. d. Pahlen have shown || that it varies with the galactic longitude of the stars. The K-term appears to consist of a constant part, which may be due to a downward convection current in high-level gases of the stellar atmospheres,¶ and of a variable part which is probably connected with the phenomena of star-streaming. A general outward streaming in the directions of the vertex (Galactic longitude 347° and latitude 0°), and in the opposite direction seems to exist alongside a general inward streaming

* *B.A.N.*, No. 23, 1922.

† "Stellar Motions," p. 202.

‡ Albrecht, *Ap. J.*, lv. 361, 1922 ; and lvii. 57, 1923.

§ *A.N.*, ccxxi. 163, 1924.

|| *Ibid.*, ccxviii. 369, 1923.

¶ Campbell, *Lick Obs. Bull.*, viii. 71, 1914 ; St. John, *Ap. J.*, lx. 48, 1924.

in Galactic longitudes 131° , 311° . The explanation of these motions, if they should be confirmed later, is yet to be found.

Further questions are raised by the distribution of radial velocities among the different spectral types. The following table, given by Plaskett,* shows this plainly:—

TABLE V
SPECTRAL CLASS AND RADIAL VELOCITY

Spectral Class.	Residual Radial Velocity.
B	6.5 km./sec.
A	10.9
F	14.4
G	15.0
K	16.8
M	17.1
N	18.0
R	21
Se	24
Me	35
O	25.5
P	30.0

That there is a relationship between a star's spectral type and its velocity in space is clear. Both, however, depend upon a third factor, namely, the mass of the star.

Halm † has shown that the correlation between stellar mass and velocity is a close approximation to that required by Maxwell's law of equipartition of energy, which enunciates that the kinetic energy of a system shall be evenly divided between the more massive and less massive members of the system, the more massive members moving more slowly. Our galactic system in the course of its evolution

* *Pub. D.A.O.*, ii, 318, 1924.

† *M.N.R.A.S.*, lxxi, 635, 1911.

has moved part way at least to a steady state in which the distribution of velocities obey Maxwell's law.* This would seem to be one fundamental point. The relation which we saw in the preceding chapter to hold between a star's mass and its absolute brightness and spectral type, when in radiative equilibrium, provides another. The observed connection between a star's spectrum and its radial velocity is a relation resulting from the dependence of these two properties of the star on its mass.

47. Spectroscopic Binaries.—It was in 1889 that E. C. Pickering announced that the doubling of the [K] line, and certain other lines in the spectrum of ζ *Ursae Majoris* (Mizar) indicated that it was a binary star with a period of 104 days.† Vogel quickly followed this announcement with a statement that the variable β *Persei* (Algol) showed a spectrum which gave a varying velocity. Further, the changes in velocity agreed with what would have been expected on Goodricke's hypothesis ‡ that *Algol* was an eclipsing binary, and that the spectrum belonged to the bright companion. Since then many hundreds of spectroscopic binaries have been discovered—for the most part at the great American and Canadian observatories.

48. Orbits of Spectroscopic Binaries.—The radial velocity of one member of a binary when plotted against the time, gives a periodic curve from which we can find the elements of the orbit (assumed elliptic) of the star relative to the centre of inertia of the binary system. In the determination of orbits for spectroscopic binaries the Canadian and American astronomers again have most results to show. It will

* The class O stars and the planetary nebulæ, being very massive and having high velocities, provide important exceptions to this Maxwellian distribution.

† *M.N.R.A.S.*, l. 296, 1890.

‡ *Phil. Trans.*, lxxiii. 482, 1783.

only be possible here to give a brief description of the methods involved.*

Take as axis of z the line from the observer to the star measuring z positive away from the observer. Take the xy plane tangential to the celestial sphere through the origin of co-ordinates, the centre of inertia of the binary system.

Let i = the inclination of the orbit plane to the xy plane taken between 0° and 90° .

ω = the longitude of periastron from the ascending node of the orbit on the xy plane, i.e. from the node at which the star is moving away from the observer.

θ = the longitude of the star from the ascending node.

v = the true anomaly of the star,

so that $v = \theta - \omega$.

a = the semi-major axis of the star's orbit round the centre of mass of the system, expressed in kilometres.

e = the eccentricity of the orbit.

$p = a(1 - e^2)$.

r = the radius vector from origin to star, expressed in kilometres.

m, m' = the masses of the star and of its companion.

Then $z = r \sin i \sin \theta$.

so that $\frac{dz}{dt} = \sin i \sin \theta \frac{dr}{dt} + r \sin i \cos \theta \frac{d\theta}{dt}$.

But if $f = km'^3/(m + m')$ where k is the Gaussian constant,

then $\frac{dr}{dt} = \frac{f}{\sqrt{p}} e \sin(\theta - \omega)$,

$$r \frac{d\theta}{dt} = \frac{f\sqrt{p}}{r} = \frac{f}{\sqrt{p}} \left\{ 1 + e \cos(\theta - \omega) \right\}$$

* For a very complete account, see "The Binary Stars," by R. G. Aitken (1918), Ch. VI. Lists of orbits which have been determined can be found in the annual reports of the Council of the R.A.S. The notation adopted is that recommended by the International Astronomical Union, *Trans. I.A.U.*, i. 22 and 170, 1922.

$$\begin{aligned} \text{so that } \frac{dz}{dt} &= \frac{f}{\sqrt{p}} \sin i [e \sin \theta \sin (\theta - \omega) \\ &\quad + \cos \theta \{1 + e \cos (\theta - \omega)\}] \\ &= \frac{f}{\sqrt{p}} \sin i (\cos \theta + e \cos \omega). \end{aligned}$$

$\frac{dz}{dt}$ is the observed velocity in the line of sight less the velocity γ of the centre of inertia of the system in the line of sight.

$$\text{Put } D = \frac{f}{\sqrt{p}} \sin i \text{ and } C = \gamma + D e \cos \omega,$$

then the observed radial velocity $\frac{dz'}{dt} = C + D \cos \theta$.

Plot $\frac{dz'}{dt}$ against the abscissa t ; a study of the measured velocities leads by a method of trial and error to a determination of the period, P , of the binary. When this has been determined as accurately as possible, all the observed values of $\frac{dz'}{dt}$ are plotted against their phase in the assumed period, and a smooth curve is drawn through the plotted points.

The curve has a maximum M_1 and a minimum M_2 .

$$\begin{aligned} M_1 &= C + D \\ M_2 &= C - D \end{aligned}$$

from which we have $C = (M_1 + M_2)/2$, $D = (M_1 - M_2)/2$. Draw on the graph a line parallel to the axis of abscissæ at a distance C above it, and measure a new ordinate Z from this line.

$$\text{We have } \frac{dZ}{dt} = \zeta = D \cos \theta.$$

Now trace the curve on to tracing paper and invert it on the line C ; move it forward half a period and find the intersections of the two curves. (One curve has to be repeated for an extra half period.) Of the 4 points of intersection, choose the two which lie on different branches of

the curve and are separated in the orbit by half the period. Then we have $\zeta_1/D = \cos \theta_1$, $\zeta_2/D = \cos \theta_2 = -\cos \theta_1$, since by the construction $\zeta_2 = -\zeta_1$. Also $\theta_2 = \theta_1 + \pi$ for the pair of points selected.

But
$$\theta_1 = v_1 + \omega, \theta_2 = v_2 + \omega,$$

$$\therefore v_2 = v_1 + \pi,$$

and these two points must correspond to periastron and apastron, the only points for which v increases by π in a half period. The steeper slope of the curve belongs to periastron, for which $v = 0$ and $\theta = \omega$ or $\zeta/D = \cos \omega$. This point determines the value of ω .

Next to determine the eccentricity of the orbit take two points at epochs t, t' (not exactly half a period apart) such that

$$\zeta = -\zeta'$$

or
$$\cos \theta = -\cos \theta'$$

i.e.
$$\theta' = \theta + \pi \text{ and } v' = v + \pi.$$

If w = the eccentric anomaly of the star corresponding true anomaly v .

P = the period

and T_0 = the epoch at periastron,

we have
$$w - e \sin w = 2\pi (t - T_0)/P$$

$$w' - e \sin w' = 2\pi (t' - T_0)/P$$

$$\therefore w - w' - e (\sin w - \sin w') = 2\pi (t - t')/P.$$

But
$$\tan \frac{v}{2} = \left(\frac{1+e}{1-e} \right)^{\frac{1}{2}} \tan \frac{w}{2}, \quad \tan \frac{v'}{2} = \left(\frac{1+e}{1-e} \right)^{\frac{1}{2}} \tan \frac{w'}{2}$$

and since
$$v' - v = \pi, \quad \tan \frac{v'}{2} \cdot \tan \frac{v}{2} = -1.$$

$$\therefore \tan \frac{w}{2} \cdot \tan \frac{w'}{2} = \frac{e-1}{e+1}$$

$$\therefore e = \cos \frac{w' - w}{2} / \cos \frac{w' + w}{2}$$

and $\therefore e (\sin w' - \sin w) = \sin (w' - w)$

i.e. substituting above

$$w' - w - \sin (w' - w) = 2\pi (t' - t)/P.$$

Put $\frac{w' - w}{2} = \eta$, $\frac{w' + w}{2} = \xi$, so that $e = \cos \eta / \cos \xi$.

Then $2\eta - \sin 2\eta = 2\pi (t' - t)/P$.

Schwarzschild published * a table giving η in terms of $(t' - t)/P$; also since $\cos (v + \omega) = \cos \theta = \xi/D$

$\therefore \eta$ and v are both known from the selected points in the figure.

$$\text{But } \tan \frac{w}{2} / \tan \frac{w'}{2} = \tan \frac{v}{2} / \tan \frac{v'}{2} = -\tan^2 \frac{v}{2}$$

$$\text{or } \sin \frac{w}{2} \cos \frac{w'}{2} / \cos \frac{w}{2} \sin \frac{w'}{2} = \left(-\sin^2 \frac{v}{2} \right) / \cos^2 \frac{v}{2}$$

$$\text{i.e. } \sin \frac{w' + w}{2} = \cos v \sin \frac{w' - w}{2}$$

$$\text{or } \sin \xi = \cos v \sin \eta$$

$\therefore \xi$ is determined, i.e. $e = \cos \eta / \cos \xi$ is known.

We cannot fully determine the orbit, the inclination and size of the major axis not being given independently in the spectroscopic orbit.

$$\text{We have } D = \frac{f \sin i}{p^{\frac{1}{2}}} = \frac{f \sin i}{a^{\frac{1}{2}}(1 - e^2)^{\frac{1}{2}}}$$

and the mean motion $= 2\pi/P = f/a^3$

whence we determine

$$a \sin i = D \frac{P}{2\pi} (1 - e^2)^{\frac{1}{2}}.$$

For the masses, again dependent on i , we have

$$\frac{m^3 \sin^3 i}{(m + m')^2} = \frac{P}{2\pi k^2} D^3 (1 - e^2)^{\frac{3}{2}}.$$

* *A.N.*, clii. 65, 1900.

If we measure m , m' in terms of the sun's mass, P in days and D in terms of km./sec., the coefficient $\frac{1}{2\pi k^2}$, comes out as 1.03×10^{-7} , so that the equation for the masses becomes

$$\frac{m^3 \sin^3 i}{(m + m')^2} = 1.03 \times 10^{-7} PD^3(1 - e^2)^{\frac{3}{2}}.$$

The above work and formulæ all apply to the motion of one star round the centre of inertia of the system. They have to be modified slightly if the motions of the two stars relative to each other are given by the spectroscopic observations.*

49. Spectroscopic and Visual Binaries.—Binary stars fall at present into two well-defined classes, the spectroscopic binaries and the visual binaries. Observational difficulties on both sides have so far prevented the gap from being filled. Michelson's stellar interferometer may have one application in filling this gap.† There are certain characteristics of the orbits of the two classes, resemblances and differences, which should be noted. The visual binaries have long periods and large eccentricities, the spectroscopic binaries have short periods and small eccentricities. The gap between the two classes is best seen from their periods. The spectroscopic periods range mostly from 0.142 d. to less than 150 days, the visual from 5.7 years upwards. The characteristics of the two classes may be shown from Table VI given by Aitken (see p. 98).‡

Further, we must note that whereas the majority of spectroscopic binaries are of B or A type,§ the majority of

* For references to the methods of improving this preliminary orbit by the method of least squares see Aitken, "The Binary Stars," p. 160.

† See Merrill, *Ap. J.*, lvi. 40, 1922.

‡ *Ibid.*, p. 196.

§ See below, Chapter VIII, for definition of spectral types.

TABLE VI
BINARY STAR CHARACTERISTICS

	Number.	Average Period.	Average Eccentricity.
Sp. Bin.	46	2.75 days	0.047
" "	19	7.80 "	0.147
" "	25	23.00 "	0.324
" "	29	555 "	0.350
Vis. Bin.	30	31.3 years	0.423
" "	20	74.4 "	0.514
" "	18	170 "	0.539

visual binaries are of G type ; in fact, none of these latter are of B type.

Again, the periods of the binaries increase steadily on the whole as the stars are classed in the order of the Harvard spectral classifications B, A, F, G, K, M. The evidence is not very clear save for the large number of B type stars of short period and the large number of G type stars of long period but, after allowing for the effect of certain observational difficulties, Aitken * sums up the evidence as, on the whole, definitely in favour of an increase of the period with advancing spectral class.

A study of the masses of binaries gives further evidence for a progressive change with spectral type. For spectroscopic binaries Aitken † gives the following table :—

TABLE VII
MASSES OF BINARY STARS

Spectrum.	m .	m' .	m'/m .
B — B8	12.3	8.5	0.69
B9 — A5	3.0	2.4	0.80
F5 — G	1.9	1.7	0.89

* "The Binary Stars," p. 200.

† *Ibid.*, p. 206.

For visual binaries of known parallax, Miller and Pitman * give the following table :—

Spectrum.	B.	A.	F.	G.	K.	M.
Average Mass	14.91	3.49	3.92	1.77	1.57	0.65

Probably the masses of the stellar components are the decisive factors in producing the relationship between spectral types and periods for binaries. Mass, absolute magnitude, and spectrum are closely related for stars as a whole, the relationship being deduced mainly from details available for components of binary stars. The secondary component of a giant is of earlier type (i.e. nearer B than M) than the primary † : on the other hand, for a dwarf star the secondary component is generally of later type than the primary. In both cases the difference in spectral type between the two components increases with the difference in their magnitudes. Components of visual binaries tend, on the whole, to be equal in mass and similar in spectral class, the tendency increasing with an increase in mass. This does not agree with what is found in the case of the spectroscopic binaries, where the mass ratio tends to differ more from unity as the total mass increases. It is one of the distinctions between the two classes of binaries pointing to some fundamental differences in their history and evolution.

50. Origin of Binaries.—Various theories have been advanced as to the formation of binary stars. Here we shall consider merely the theory of formation by fission from a parent body, originally a rotating nebula. The

* *A.J.*, xxxiv. 131, 1922.

† Leonard, *Lick Obs. Bull.*, No. 343, 1923 ; Doig, *M.N.R.A.S.*, lxxxii. 322, 1922.

process of development has been sketched by Jeans.* In the process of contraction with consequent increased rotation a stellar nucleus, formed in an arm of a parent nebula, may first lose matter by ejection of jets from its own equator. A surrounding atmosphere may be formed at the expense of the central mass, whose condensation continues. A spheroidal, then an ellipsoidal, shape is assumed by this condensing nucleus which later becomes pear-shaped and finally may break up into two detached masses. It is very difficult to see how this process of development can apply to the giant binaries of low density, but it may well apply to the dwarfs. After fission tidal friction may well operate to cause (1) increasing separation ; (2) increasing period ; and (3) increasing eccentricity.† This is well in accord with the facts discussed in the last paragraph so far as dwarf binaries are concerned. But we may not assume that every individual binary passes through the whole range of values given by the spectroscopic and visual binaries, if the development is to be traced to forces originating inside the binary system. Dynamically such a course is impossible. To secure an explanation of the observed phenomena as representing one chain of development, Jeans suggests that the visual binaries of late spectral type date from an epoch when stars were more closely packed than is now generally the case. Their development along the lines of increasing separation and eccentricity is to be traced mainly to the effects of encounters with other stellar systems. The B-type spectroscopic binaries were born at a later epoch and probably by some other process than that of the simple fission of a parent nucleus ; by the time of their birth our galaxy had opened out and stellar encounters had become less frequent.

* " Problems of Cosmogony," Jeans, 1919. The reader is referred to this book for the most complete mathematical treatment of the question as yet available.

† See Table VI, § 49.

These binaries could have changed but slightly in period and eccentricity since their birth, and are not likely to change much in the future. The evolution which has left its mark on binary systems of earlier date belongs to a distant past. The present processes are slow and will not provide many changes of great importance. It is true that the components of the giant spectroscopic binaries may themselves break into two, providing triple and multiple systems. Such systems are known both from visual and spectroscopic observations, and the types of systems known agree on the whole well with the requirements of the theory of fission.* But, apart from this, marked changes in binary systems are unlikely, unless, in due course, our universe or portions of it pass once more through a stage where stars are more closely packed than at present. Smart has pointed out † that loss of mass accompanying radiation would allow *very massive* spectroscopic binaries to evolve into dwarf visual binaries; to that extent the general views of Jeans given above need modification.

* Russell, *Ap. J.*, xxxi. 200, 1910.

† *Observatory*, xlviii. 95, 1925.

CHAPTER VIII

STELLAR CLASSIFICATION

51. Early Work—(a) *Secchi's Types*.—Secchi was the first * to form a simple framework into which to fit his observed spectra. He suggested four types as sufficient, and we may note that his classification was empirical, being independent of any theory of evolution. His grouping was as follows :—

Type I. White or blue stars. The presence of dark hydrogen lines and the absence or the faint presence only of metallic lines are to be noticed. Typical stars are *α Canis Majoris* and *α Lyræ*.

Type II. Yellow stars. These stars have a great number of fine dark lines in their spectra. Typical stars are the sun, *α Aurigæ*, and *α Boötis*.

Type III. Red and orange stars, including most of the variable stars. These stars have numerous dark bands or flutings, sharp on the violet side and fading away towards the red. Typical stars are *α Orionis*, *ο Ceti*, *α Scorpii*, *α Herculis*.

Type IV. Faint stars of a deep red colour, whose flutings shade off in the opposite direction to those of Type III stars. Typical stars are *152 Schjellerup*, *19 Piscium*.

Type V was suggested later by E. C. Pickering † to include the bright-lined Wolf-Rayet stars and the planetary nebulæ.

(b) *Vogel's Classes*.—The next important classification

* *C.R.*, lxiii. 621, 1866.

† *A.N.*, cxxvii. 1, 1891.

was Vogel's,* based on a definite view of the orderly development of stars in time from one spectral stage to another. The word "class" is used of Vogel's scheme, the word "type" applying to Secchi's work. The chief difference from Secchi's scheme was in the subdivision of the classes and the re-numbering of Secchi's Types III and IV as Classes III (a) and III (b) respectively. Vogel's view was that the difference between these two types was not generic enough to justify their being placed in separate classes. Pickering's Type V was placed by Vogel in Class II (b).

Following the sequence now generally adopted, we may give Vogel's classification briefly as follows:—

Class II (b). The bright-lined Wolf-Rayet stars (see below, Harvard Class O ; Type V).

Class I_{c1}. Stars with bright hydrogen lines (but without the characteristic Wolf-Rayet bands).

Class I_{c2}. Stars as in the previous class, but with bright metallic enhanced lines also present.

These two classes represent peculiar spectra that really lie outside the main schemes of classification.

Class I_b. The helium, or so-called "Orion" stars, with strong dark helium and hydrogen lines. Absorption lines due to carbon, oxygen, and nitrogen are also present and strong. A few enhanced lines of metals also present (Class B ; Type I).

Class I_{a1}. Hydrogen lines present alone. Probably not a true class.

Class I_{a2}. Hydrogen present and the metallic lines much stronger and more frequent than in Class I, b. Helium absent (Class A ; Type I).

Class I_{a3}. The [K] line of calcium as strong as the hydrogen lines (Classes A₅, F₀, F₅ ; Type I).

Class II (a). The hydrogen lines lose their prominence

* *A.N.*, lxxxiv. 113, 1874 ; *Ap. J.*, ii. 333, 1895.

among the numerous metallic lines (Classes F8, G, Ko, K2 ; Type II).

Class III (a). Yellowish-red and reddish stars with dark bands, sharp on the violet side and shading off towards the red (Classes K5, M, S ; Type III).

Class III (b). Stars of a deep red colour with carbon bands shading off towards the violet (Classes R, N ; Type IV)

(c) *Harvard Classes*.—In the Draper Catalogue,* Pickering and his colleagues at Harvard developed a scheme, using the letters A, B . . . Q to denote different spectral classes. Miss Cannon † modified this scheme by adding to each class numbers 0, 1 . . . 9, to allow of grading of classes and intermediate stages. Thus F₃G—or more shortly F₃—indicates that a star is three-tenths of the way from a typical F or F₀ star to a typical G or G₀ star. The behaviour of certain *bright* lines or bands was used by Miss Cannon in further subdividing the Harvard classes, the notation employed being of the type Md, Oa. In the latest Harvard Catalogue, the new Henry Draper Catalogue,‡ which gives the spectra of all stars down to the ninth magnitude the letters P, O, B, A, F, G, K, M, N, R, S and Q alone survive in use. Details are given below in § 54.

An entirely different scheme of classification was attempted also at Harvard by Miss Maury.§ She divided the stars into twenty-two groups, which she subdivided again by the affixes *a*, *b*, *c*, according to the behaviour of certain *dark* lines in the spectrum. Recently it has been pointed out that her affix *c*, indicating the presence of unusually sharp lines, corresponds to a condition of low density, typical of the giant stars. Her sub-class *b* denoted spectra with unusually broad and diffuse lines, sub-class *c* spectra with unusually sharp lines, and sub-class *a* intermediate

* *Harvard Annals*, xxvii. 1890.

† *Ibid.*, xci.-xcix. 1918-24.

‡ *Ibid.*, xxviii. Part II, 1901.

§ *Ibid.*, xxviii. Part I, 1897.

spectra. It may be useful to give here the connection between the two Harvard schemes, so that the frequent references to Miss Maury's scheme in astronomical literature can be readily referred to the Draper classification.

TABLE VIII

HARVARD CLASSIFICATIONS

Maury's Group.	Draper.	Maury's Group.	Draper.	Maury's Group.	Draper.
I	Oe5	IX	A ₂	XVI	K ₅
II	Bo	X	A ₅	XVII and XVIII	Ma or Mo
III	B ₁	XI	F ₀	XIX	Mb or M ₃
IV	B ₂	XII	F ₅	XX	Md or Me
V	B ₅	XIII	F ₈	XXI	N
VI	B ₈	XIV	Go	XXII	O (Wolf-Rayet)
VII and VIII	Ao	XV	Ko	—	—

(d) Further schemes which must be mentioned are McClean's six divisions * and Sir Norman Lockyer's two schemes.† The latter provided alternatively six groups (I to VI), which he then subdivided, or more usually a scheme of 16 groups called after some typical star, e.g. Polarian, Algolian. The fundamental ideas of Lockyer's scheme—that the stars of a given spectral type must be divided into two classes according as they belong to the branch of ascending or descending temperature in the evolution scale—came later to be generally accepted, even though the actual details of his subdivisions have not been generally adopted.

A comparison between the Draper Classes and the Lockyer groups shows a good deal of cross grouping,‡ and indicates the following as the best comparison table :—

* *Phil. Trans.*, cxc. 127, 1897.

† *Ibid.*, clxxxiv. 675, 1892, and *Proc. R.S.*, lxxv. 186, 1899.

‡ *Hill Obs. Bull.*, No. IV, 191.

TABLE IX

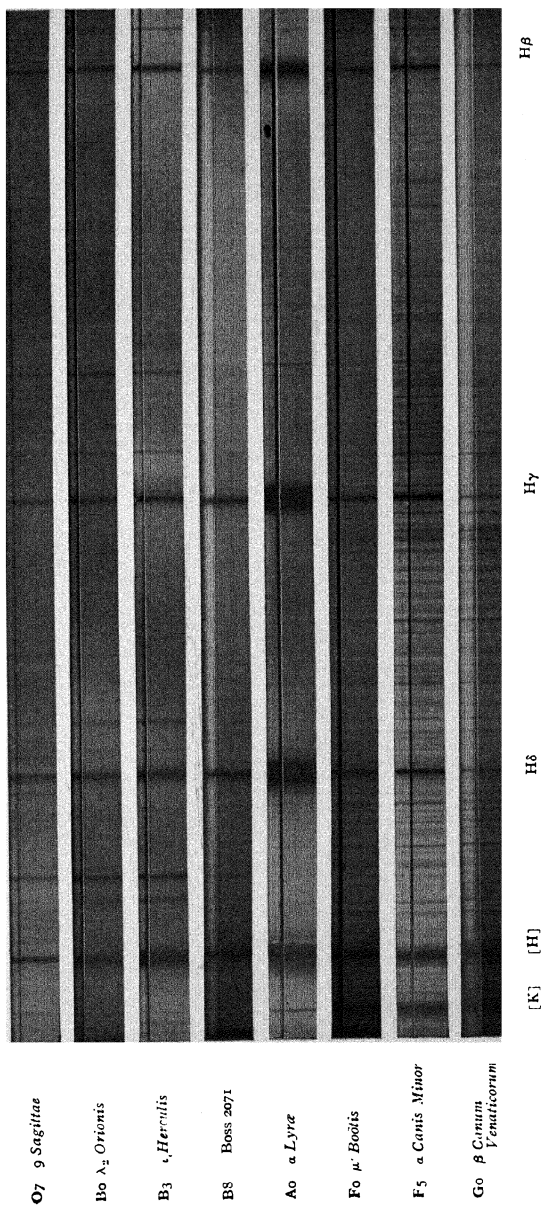
LOCKYER'S SPECTRAL TYPES

Ascending Temperatures.		Descending Temperatures.	
Lockyer.	Harvard.	Lockyer.	Harvard.
Antarian	M	Piscian	N
Aldebarian	G, K	Arcturian	G, K
Polarian	F ₂	Procyonian	F ₅
Cygnian	A ₂	Sirian	A
Rigelian	B ₉	Markabian	A
Taurian	B ₃	Algolian	B ₈
Crucian	B ₃₋₂	Achernian	B ₃
	Alnitamian B ₂		
	Argonian O		

We may note that the extension of the spectrum made available for examination by the use of photography has not affected very much the main classification schemes worked out by the early visual observers, although it may have modified the placing of individual stars in different transition groups. An idea of the chaotic condition of spectral classification in the earlier work may be given by the following list of designations for the star Procyon:—

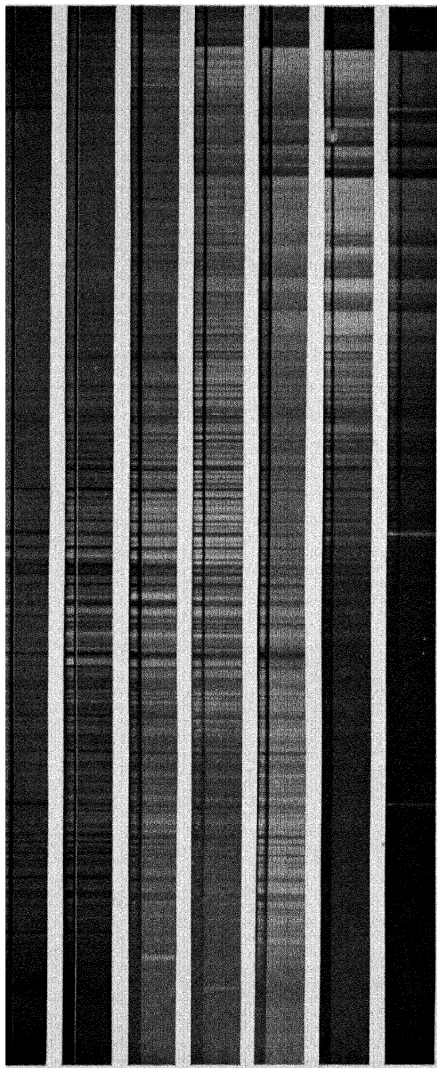
Secchi	Type I
Vogel	Class I(<i>a</i>) and later Ia ₃
Pickering	F
Miss Cannon	F ₅ G or F ₅
Miss Maury	XII A
McClean	Division III
Lockyer	{ A (β) 3 or Group V { Procyonian

52. Nature of Classification Sequence.—The above-mentioned schemes of classification depend on variations in the main features of the stellar spectra. It is remarkable in how small a number of different types we can include the



TYPICAL STELLAR SPECTRA—EARLY TYPES

In each case the untouched stellar spectrum is placed immediately above the artificially widened spectrum, so that false lines in the latter may be recognised as such. The spectrograms were obtained with the 72-inch reflector of the Dominion Astrophysical Observatory, Victoria, B.C.



Gr t *Persei*

Ko γ *Andromedæ*

K5 α *Hydræ*

M1 α *Orionis*

M7 R *Lyræ*

M8 40 *Coronæ Borealis*

Me o *Ceti*

H δ

H γ

H β

TYPICAL STELLAR SPECTRA—LATE TYPES

In each case the untouched stellar spectrum is placed immediately above the artificially widened spectrum, so that false lines in the latter may be recognized as such. The spectrograms were obtained with the 72-inch reflector of the Dominion Astrophysical Observatory, Victoria, B.C.

great majority of the stars. Over 99 per cent. of the stars fall into one or other of the Harvard classes B, A, F, G, K and M. And it is noteworthy that inside these types the stars form a *linear* sequence. Only one physical condition has to be looked for whose variation from star to star is accompanied by changes in the stellar spectra. Differences of temperature are generally accepted as providing the chief reason for differences in spectra. We are not here concerned with underlying factors that govern the temperature nor with the manner in which the temperature governs the resulting spectrum. Our interest here lies mainly with the spectral sequence itself O-B-A-F-G-K-M (with the alternative endings G-S or G-R-N), which runs in the order of descending temperatures (Plates 23, 24). We have, at first the Balmer series of hydrogen and lines due to ionized helium, the spectra frequently containing some bright lines. The bright lines vanish and fresh, strong dark lines, due to ionized nitrogen, silicon, carbon, and oxygen develop, apparently in that order—the true order may be fixed when we have full knowledge of the series relationships of the lines concerned and the ionization potentials* of the elements. These lines weaken and we get lines due to non-ionized helium strengthening along with lines due to magnesium, iron, calcium, titanium, strontium, etc. Most of these lines come from ionized atoms of the elements. Helium vanishes and arc lines of the metals strengthen at the expense of the spark lines, i.e. lines due to the neutral atom replace those due to the ionized atom. Fresh elements make their appearance and finally, along one of two or three main lines, we find bands of compounds appearing in the spectra.

We give briefly the classes of the Draper Catalogue, as

* The ionization potential is the number of volts through which an electron must fall in order to acquire the energy necessary to ionize a single molecule of the gas.

defined in the sequence of these chemical changes. In Class O₅ we find the *He* II lines at their strongest, and we get evidence of *N* III at 4634, 4642. In Class O₇ *N* III 4097 is at its strongest, and *Si* IV 4089 is well present, as also *O* III 4647: *He* I is stronger than *He* II. In Class O₉ we get *O* III 3962 at its strongest, *Si* IV 4089 very strong, and *Mg* II 4481 well present. In Class B₀ the *He* I lines and the *Si* III lines at 4552·6, 4567·8, 4574·7 are becoming fairly strong. The *Si* IV and the *C* III lines are at maximum strength, and we get the first traces of the line [K], *Ca* II 3933·7. In Class B₁ the *Si* III lines at 4552·6, 4567·8, 4574·7 and the *He* I lines are stronger than the *Si* IV and *C* III lines so prominent in Class O₉, the *Si* III lines reaching maximum strength in Classes B₁, B₂. By this time the line at 4650 is mainly due to *O* II 4649·1; *O* II is at its strongest about this stage. In Class B₂, the *He* I lines are at maximum, being next in strength to the hydrogen lines which are paramount throughout the B class. In Class B₅ a new set of lines begin to be prominent, of which we may mention *Si* II 4128, 4131, and *Mg* II 4481·2, as well as *Ca* II 3933·7. These and other enhanced lines strengthen in Class B₈, the *Si* II lines 4128, 4131 being at their strongest; most of the *He* I lines are also still strong. At this stage *He* I drops rapidly out, showing a few lines in Class B₉ and being practically gone in Class A₀. At this stage the spectrum is mainly hydrogen and enhanced metallic lines, but the stronger arc lines begin to appear, and in Class A₂ we find the line *Ca* I 4227. The chief changes now are the growing importance of arc lines of metals relative to the spark lines and to hydrogen; by the time we come to Class F₅ we find the arc lines of iron and titanium about of equal strength with the enhanced spark lines, the [g] line, *Ca* I 4227, very well marked and the hydrocarbon band [G] just beginning. As we pass along the sequence other elements such as vanadium begin to appear, this

element being strongly represented in Class K₅. The titanium oxide bands also begin to appear at this point, the main sequence leading to Class M. Meanwhile, at an earlier stage, G₅, carbon bands had begun to appear in a few stars leading in a steady sequence to Classes R and N; at a point not yet determined in the main sequence, we may have to fit in another branch containing stars showing bands of zirconium oxide, Class S.

In the above paragraph, though we have followed the usual sequence of spectra and spoken of one set of lines developing and replacing others, there is no time sequence to be thought of as invariably accompanying the spectral sequence in one direction. As we shall see in the following chapter, a view now widely held is of a double sequence from "late" to "early" and back to "late" classes again. The subject of stellar evolution will be discussed in a later chapter.

53. Adopted Classification.—At the meeting of the International Solar Union held at Mount Wilson in 1910, a Committee was appointed on the classification of stellar spectra in the hope that the confusion arising from the use of the many existing systems might be ended. The views of the members of the Committee proved, on inquiry, to be generally in favour of retaining the Draper classification as the basis of a system for universal adoption.* This view was confirmed at the meeting, in 1922, of the International Astronomical Union at Rome. The Harvard system was adopted for general use with modifications and additions to the notation where required for special technical researches. We give below details of the Harvard classification as given by Miss Cannon in the Henry Draper Catalogue, † together with notes on some of the more important additions adopted by the International Astronomical Union. For convenience

* *Ap. J.*, xxxiii. 260, 1911.

† *Harvard Annals*, vols. xci.-xcix, 1918-24.

of reference, Miss Cannon's classification of planetary nebulae is added, but on this subject the reader is referred to § 66 below.

54. Draper Classification.—Class Pa. The double line 3726, 3729 is more conspicuous than the chief nebular lines 5007, 4959. Typical nebula, I.C. 418, R.A. 5 h. 22.8 m., Dec. — $12^{\circ} 46'$. [*Equinox here and throughout this paragraph 1900.0.*]

Class Pb. The lines 5007, 4959 are stronger. Typical nebula, the Great Nebula of Orion.

Class Pc. The line 4363 is the most conspicuous. Typical nebula, I.C. 4997, R.A. 20 h. 15.6 m. Dec. + $16^{\circ} 25'$.

Class Pd. The chief nebular line 5007 is the strongest line. Typical nebulae, N.G.C. 6826, R.A. 19 h. 42.1 m., Dec. + $50^{\circ} 17'$ and N.G.C. 6326, R.A. 17 h. 12.9 m., Dec. — $51^{\circ} 40'$.

Class Pe. The line *He* II 4685.7 is also present. Typical nebulae, N.G.C. 7662, R.A. 23 h. 21.1 m., Dec. + $41^{\circ} 59'$, and N.G.C. 7009, R.A. 20 h. 58.7 m., Dec. — $11^{\circ} 46'$.

Class Pf. A bright band centred at 4650, probably due to carbon, is the most conspicuous feature of the spectrum. Typical nebula, N.G.C. 40, R.A. 0 h. 7.6 m., Dec. + $71^{\circ} 32'$.

Class Oa. A broad, bright band, centred at 4650, is the most conspicuous feature of the spectrum. *H γ* and *H δ* are bright, and several other bright bands are seen, but not the typical nebular lines such as 4363 or 5007. Typical stars, B.D. + $35^{\circ} 4013$, R.A. 20 h. 8.2 m., Dec. + $35^{\circ} 54'$ and C.P.D. — $60^{\circ} 2578$, R.A. 11 h. 5.8 m., Dec. — $60^{\circ} 26'$.

Class Ob. A wide, bright band, centred at 4686 is the most characteristic feature, the hydrogen lines *H β* , *H γ* , *H δ* , are bright, and also the helium lines of the ζ *Puppis* series (see Class Od below). Typical stars, B.D. + $35^{\circ} 4001$, R.A. 20 h. 6.5 m., Dec. + $35^{\circ} 53'$ and C.D.M. — $23^{\circ} 4553$, R.A. 6 h. 50.0 m., Dec. — $23^{\circ} 48'$.

Class Oc. The bands are narrower, and two well-separated lines are seen at 4686 and 4638, the former due to

ionized helium being twice as bright as the latter, due to ionized nitrogen (4634, 4642). The hydrogen lines and the ζ *Puppis* lines are bright. *No dark lines are seen. Typical stars, B.D. + 36° 3987, R.A. 20 h. 13.3 m., Dec. + 37° 7', and C.D.M. — 41° 10972, R.A. 16 h. 45.3 m., Dec. — 41° 41'.

Class Od. All lines are dark except 4686 and 4638, which are bright. Seven dark lines of the ζ *Puppis* series (ionized helium) at 5412, 4542, 4200, 4026, 3924, 3858, 3815 have been photographed, and the line *He* I 4471.5 is now seen. Typical stars ζ *Puppis* and λ *Cephei*. From here to the early Class A stars the dark hydrogen lines are paramount.

Class Oe. This represents a transition stage from Pickering's Type V to Secchi's Type I. All lines are dark except *He* II 4686 and *N* III 4634, 4642, the two latter lines being the probable source of a bright band at 4638; hydrogen lines and numerous helium and other dark lines are present, notably *Si* IV 4089 and *N* III 4097.* Typical star, 29 *Canis Majoris*, R.A. 7 h. 14.5 m., Dec. — 24° 23'.

Class Oe 5. Intermediate between Oe and Bo. No bright bands are seen, but the ζ *Puppis* series is present, and strong as in Class Oe. The lines *He* I 4026 and 4471.5 are strong as also the line *He* II 4686; a line at 4650, probably *C* III, is strong. Typical star, τ *Canis Minoris*.

Class Bo. The hydrogen lines strengthen, and the ζ *Puppis* series weaken. The lines *C* III 4647, 4650 are strong, and the triplet *O* II 4070, 4072, 4076 is growing in strength. The lines *Si* IV 4089, 4116, are at their greatest intensity. The lines *He* I 4026, 4471.5 are of equal strength, but less intense than the line at 4650, now probably a blend of oxygen and carbon. Typical star, ϵ *Orionis* (Alnitam).

Class B1. The Balmer series of hydrogen can be followed

* For the evidence that these lines are due to silicon atoms with three electrons removed and nitrogen with two electrons removed, see Fowler, "Report on Series in Line Spectra," p. 164 (Physical Society of London, 1922), *Proc. R.S.*, ciii. A, 413, 1923, and *Phil. Trans.*, ccxxv. A, 1, 1924.

up to H γ . The ζ *Puppis* series cannot be distinctly seen. Trebly ionized silicon, and doubly ionized carbon are fainter, while helium grows stronger, *He* I_{4471.5} exceeding *O* II 4649 in intensity; as also *He* I 4121 exceeds *Si* IV 4116. The lines *Si* III 4552, 4568, 4574 are reaching maximum strength. Typical stars, β *Canis Majoris* (Mirzam) and β *Centauri*.

Class B2. The lines of helium reach maximum intensity, the trebly ionized silicon and the ionized oxygen lines are much weaker; *Si* IV 4116 is not seen. Typical stars, γ *Orionis* (Bellatrix) and α *Lupi*.

Class B3. The hydrogen lines strengthen appreciably, but the helium lines stand out prominently owing to the disappearance or extreme faintness of the oxygen and silicon lines. The strongest helium lines are 3820, 4009, 4026, 4144, 4388, 4471.5, and 4922. Typical stars, π^4 *Orionis* and α *Pavonis*.

Class B5. *Ca* II 3933.7 [K] becomes stronger, as also the double, *Si* II 4128, 4131; this double is now intermediate in strength between the helium lines 4121 and 4144, the last-named being the strongest of the four lines. *Mg* II 4481 is 0.7 times as intense as *He* I 4471.5. Typical stars, η *Tauri* and ϕ *Velorum*.

Class B8. The lines *He* I 4026 and 4471.5 are present, the latter being equal in strength with *Mg* II 4481; *Ca* II 3933.7 [K] is weaker than *He* I 4026. Several of the lines due to ionized metals, prominent in Class A0 are present. Typical stars, β *Persei* and γ *Gruis*.

Class B9. The spectrum is almost the same as that of Class A0, except that *He* I 4026 is seen, and [K] is somewhat fainter than in Class A0. Typical stars, λ *Aquilæ* and λ *Centauri*.

Class A0. The hydrogen lines are at maximum intensity; [K] is about one-tenth as intense as H δ ; *Su* II 3968.5, [H], is separated from H ϵ . *Mg* II 4481 is next strongest to [K] and the hydrogen lines. Many metallic lines are

present. The lines Si II 4128, 4131 are at maximum strength.* Typical star, α *Canis Majoris* (Sirius).

Class A2. [K] is nearly half as intense as H δ . The lines Mg II 4481, Ca I 4227, Fe II 4233 are well marked, the two latter being of nearly equal strength. No helium lines are seen in this or any following class. Typical stars, δ *Ursæ Majoris* and α *Centauri*.

Class A3. [K] is more than half as intense as the compound line, [H] and H ϵ , and is four-fifths as intense as H δ . The metallic lines are more numerous and stronger than in Class A2, while the hydrogen lines are slightly fainter. Typical stars, α *Piscis Austrini* (Fomalhaut) and T³ *Eridani*.

Class A5. [K] is now stronger than H δ , and nearly as strong as the blend of [H] and H ϵ . Mg II 4481 is no longer the most conspicuous of the other lines. Lines at 4300, due to iron and ionized titanium and iron, are well marked. Typical stars, β *Trianguli* and α *Pictoris*.

Class F0. The hydrogen lines are now about half the strength of those in class A0. [K] is as strong as [H] and H ϵ combined, and three times as strong as H δ . The iron, titanium and calcium lines 4305-09 are faint and inconspicuous. Typical stars, δ *Geminorum* (Wasat) and α *Carinæ* (Canopus).

Class F2. The lines 4305 to 4315 increase in strength, suggesting a continuous dark band where, in later classes, we find the hydrocarbon [G] band. Typical star, π *Sagittarii*.

Class F5. Ca I 4227, [g], is well marked among numerous lines, but it is not half as strong as H γ ; Fe 4326 is about one-tenth as intense as H γ . The blend at 4309 is more intense than the iron and titanium blend at 4315. The hydrogen lines are twice as strong as in Class G0 (solar type), while the metallic lines are fainter and less numerous than

* Payne, *H.C.O. Circular*, 252, 1924.

in Class Go. The band [G] is probably just present. This Class represents the transition stage from Secchi's Type I to Type II. The hydrogen lines are still predominant; the typical star, α *Canis Minoris* (Procyon), was classed by Secchi as Type I. The southern typical star is ρ *Puppis*.

Class F8. Intermediate between Classes F5 and Go in the strength of the hydrogen lines and a few of the metallic lines. Otherwise it closely resembles Class Go. Typical stars, β *Virginis* and α *Fornacis* (Zavijava).

Class Go. The solar type of spectrum. The hydrogen lines no longer stand out conspicuously as a series. $H\gamma$ is now only half as intense again as *Fe* 4326. The iron and strontium blend at 4077, $H\delta$ and *Ca* I 4227 are nearly equal in intensity. The broad dark lines [H] and [K] are very conspicuous. The continuous spectrum is nearly constant in intensity from $H\beta$ to $H\epsilon$, but there is a slight gradual falling off from $H\gamma$ to $H\epsilon$. Typical stars, α *Aurigæ* (Capella) and β *Hydri*.

Class G5. The hydrogen lines are slightly fainter than in Class Go. $H\gamma$ is now fainter than *Fe* 4326. The lines *Si* I 3905, 4103 are at maximum strength. The distribution of light becomes less even. Typical stars, κ *Geminorum* and α *Reticuli*.

Class Ko. The sunspot spectrum. The hydrogen lines are fainter than in Class G5, $H\gamma$ being only half the intensity of *Fe* 4326. The line *Ca* I 4227, [g], is three times as strong as in Class Go and is three times as intense as the iron double 4383-5. The hydrocarbon band [G] is continuous from 4299 to 4315, and is more conspicuous than the line [g]. Several portions, such as 4077- $H\delta$, 4215-4227, 4470-4525 and 4614-4648 appear brighter than adjacent parts, and the continuous shows a decided decrease from $H\gamma$ to $H\epsilon$. The dark lines at [H] and [K] reach their greatest intensity. Typical stars, α *Boötis* (Arcturus) and α *Phœnicis* (Nair al Zaurak).

Class K2. The calcium line [g] is stronger, but the [G] band is still continuous. The continuous spectrum is fainter towards the end of shorter wave-lengths. Typical stars, β *Cancris* and ν *Librae*.

Class K5. The most conspicuous lines are [H], [K], and [g]. The [G] band is no longer continuous. The two blends *Fe* 4383-5 and *Fe, Va*, 4405-8 form a conspicuous pair, the former being the stronger. The absorption bands of Class M begin to appear in the form of breaks in the continuous at 4761, H β , 4955 and 5167. Typical star, α *Tauri* (Aldebaran). This class represents the transition stage to Type III.

Class Ma or Mo.* The spectrum is banded, the bands being due to titanium oxide.† The strongest absorption bands have heads at 4762, 4954, 5168, 5445. Bright spaces are seen, such as 4556-4586, 4657-4668. Owing to the faintness of the continuous spectrum towards the shorter wave-lengths [H] and [K] are barely visible. *Ca* I 4227, [g], is the most conspicuous absorption line. The lines of the [G] band are well separated, and *Fe* 4315 is very faint. Typical stars, α *Orionis* (Betelgeuse) and γ *Hydri*.

Class Mb or M3. The edges of the absorption bands mentioned in the previous class are strong, and appear like bright bands. *Ca* 4227 is very wide and intense. Only blends at 4300 and 4306 remain well marked in the position of the band [G]. Conspicuous bright bands show at 4556-4586, 4614-4626. Typical stars, ρ *Persei* and γ *Crucis*.

Class Mc or M8. The continuous spectrum is fainter, and the bright-edged bands stronger, than in the two preceding classes. The spectrum appears fluted. Typical stars, W *Cygni* and R X *Aquarii*.

* A modification approved by the International Astronomical Union at Rome, 1922.

† Fowler, *Proc. R.S.*, lxxiii, 219, 1904. *M.N.R.A.S.*, lxxix, 508, 1909.

Class Md.* This class consists of stars of Class M, in which at least one hydrogen line is bright. It includes the greater number of the long period variables, though the spectra differ widely in detail. Typical stars, χ *Cygni* and *o Ceti* (Mira).

Class Ro.† This and the following classes belong to Secchi's Type IV. The distribution of light resembles that in Classes G5 or Ko, the broad absorptions at [H] and [K] being well seen. A dark carbon band at 4737 (centred at 4700) is wide and strong, and a dark blend (probably of titanium, vanadium, and iron) at 4395 is about equal in strength to the [G] band. The dark bands in this and the next few classes down to N3 are due to compounds of carbon. There are well-marked lines at *Ca* I 4227 and at *Fe* 4234, 4236, and 4239. Typical star, S.D. — $10^{\circ} 5057$, R.A. 19 h. 17.6 m., Dec. — $10^{\circ} 54'$.

Class R3. The [H] and [K] lines are visible, but fainter than in Class Ro, the continuous spectrum to the violet of H γ being only about half as intense as for Class Ro. Typical star, B.D. + $5^{\circ} 5223$, R.A. 23 h. 44.0 m., Dec. + $5^{\circ} 50'$.

Class R5. The continuous spectrum for wave-lengths shorter than 4240 is barely visible save for very long exposures. There are three bright regions of increasing intensity centred at 4300, 4400, 4840. Typical star, S.D. — $3^{\circ} 1685$, R.A. 6 h. 56.1 m., Dec. — $3^{\circ} 6'$.

Class R8. The spectrum is very faint to the violet of 4240. The spectrum closely resembles that of Class No. Typical star, B.D. + $61^{\circ} 667$, R.A. 3 h. 57.2 m., Dec. + $61^{\circ} 31'$.

* The International Astronomical Union proposes that this symbol should be replaced by the symbols M0e, M1e, M2e . . . M8e. For details of this spectral class see Merrill, *Pub. of the Obs. of the Univ. of Michigan*, ii. 45, 1916, and *Ap. J.*, lviii, 215, 1923.

† See Rufus, *Pub. of the Obs. of the Univ. of Michigan*, ii. 103, 1916.

Class Na or No.* The spectrum between 4240' and [K] is even fainter than for Class R8. The three bright regions of Class R5, which have for that class respective intensities 3, 6, 10, have for class No intensities 0, 8, 10. Typical star, 19 *Piscium*, B.D. + 2° 4709, R.A. 23 h. 41.3 m., Dec. + 2° 56'.

Class Nb or N3. We may estimate the respective intensities of the three bright portions found in the preceding classes as 0, 6, 10. Typical star, B.D. + 67° 350, R.A. 4 h. 40.8 m., Dec. + 67° 59'.

Class S † This class contains many long period variables and other red stars which resemble neither Class M nor Classes R and N. Absorption bands are present at 4650 and 6470, while the spectrum between 4500 and 4700 is very complicated with absorption and emission lines. The absorption bands have been identified with those of zirconium oxide. Most of the stars in this class have bright hydrogen lines, and they appear to represent a third branch of spectral sequence similar to the G — K — M and G₅ — R — N branches. Typical stars, π^1 *Gruis*, R *Cygni*, and R *Andromedæ*.

In connection with this account of the Draper Classification, taken from the Henry Draper Catalogues, it is convenient to make a few comments. The terms "early" and "late" are regularly used of stellar spectra referring to the positions of stars in the spectral sequence O — B — A — F — G — K — M. It is unfortunate that this custom was started when it was generally believed that this sequence corresponded to the order of evolution. The terms have proved very convenient and will probably remain in use as a method of dividing the spectral sequence into two portions. It must be remembered, however, in

* See Hale, Ellerman and Parkhurst, *Pub. of the Yerkes Obs.*, ii, 251, 1903.

† Merrill, *Ap. J.*, lvi. 457, 1922.

this connection that they do not carry with them their usual time significance and do not correspond to early and late stages in the evolution of a star.

A modification of the Draper Classification, which has been adopted by some writers, consists of the replacement of the Classes Oa, . . . Oe, by classes with numerical affixes as in the rest of the scheme. This will have to be done eventually from criteria based on the temperature or ionization of the stellar atmospheres. A start has been made by H. H. Plaskett in his study of three O-Type stars.* He rejects the Harvard sub-divisions of Class O in terms of bright bands, and suggests the substitution of criteria in terms of the presence or absence of certain dark lines. His suggested scheme is as follows :—

Class Oo. The ionized helium lines found in ζ *Puppis* are not visible. No typical star of this class is known.

Class O5. The ζ *Puppis* ionized helium lines present and at their strongest relative to the Balmer series of hydrogen. *He* II 4542 is 0.6 times as intense as *H γ* . *N* III 4634, 4642 just seen. Typical star, B.D. 35° 3930, R.A. 19 h. 59.8 m., Dec. + 35° 45'.

Class O6. *He* II 4542 now half as strong as *H γ* . *He* I 4471.5 now seen, but not so strong as *He* II 4542. *Si* IV 4089 present, but weak and not so strong as *N* III 4097. Typical star, B.D. 44° 3639, R.A. 20 h. 53.1 m., Dec. + 44° 33'.

Class O7. *He* I 4471.5 stronger than *He* II 4542, which is now only 0.4 times as strong as *H γ* . *Si* IV 4089 strengthening compared with *N* III 4097, which is at its maximum strength. *C* III 4647 now present. Typical star, η *Sagittae*.

Class O8. *He* I 4471.5 now twice as strong as *He* II 4542 and other *He* I lines at 4121, 4144, 4388, 4713,

* *Pub. D.A.O.*, i. 325, 1922. For a fuller study of O-Type stars see J. S. Plaskett, *Pub. D.A.O.*, ii. 287, 1924.

quite strong. *Si* IV 4089, *N* III 4097, of equal strength, the silicon having strengthened and the nitrogen weakened. The *C* III triplet at 4647 is stronger. *Mg* II 4481 just appears. Typical star, λ *Orionis*.

Class O9. Lines generally sharper. *Si* IV 4089, 4116 reach their maximum, while *Si* III 4552, 4568 are just appearing. *Mg* II 4481 is stronger. Doubly ionized carbon is stronger, but not yet at maximum strength. The *O* III lines at 3962, 5592 are strong. Helium is strengthening relative to hydrogen and still more relative to ionized helium. Typical star, 10 *Lacertæ*.

For Wolf-Rayet stars with bright lines, the Classes O5 to O9 may be used with the affix e to denote the presence of emission (see § 55 (9) below).

55. Notation for Special Spectra.—The International Astronomical Union has adopted a number of modifications of the notation of the Henry Draper Catalogue in order to deal with special cases. A few of these are given below.

(1) Composite spectra should be denoted by the sign + connecting the two superposed types, as *K0* + *B9*, the same notation being used for an eclipsing variable whose spectrum varies more or less discontinuously.

(2) In the case of such stars as Cepheid variables, where the spectrum varies continuously, it should be recorded as, for example, "F7 to G4." If one spectrum only is given for a variable star it should be the spectrum at maximum.

(3) The prefix c should be used for exceptionally bright stars which normally have all lines narrow and sharp. In the c-stars later than A0 the hydrogen and the enhanced metallic lines are abnormally strong compared with their general spectral type. *Ca* I 4227 is abnormally weak when compared with *H γ* or with *Sr* II 4216. The stars should be called c-stars and the prefix should not be used for stars of class earlier than B0. Typical stars, ϵ *Canis Majoris*, cB1; *a Persei*, cF5; and *a Scorpii* cM0.

(4) The prefix *g* should be used for ordinary giant stars of Class F₀ or later which have the enhanced lines and the hydrogen lines strong for their spectral type, and the low-temperature lines relatively weak. For Class F *Sr II* 4077 and 4216, *Ti II* 4290 are strong; for Classes G, K, M *Sr II* 4077 and 4216 are strong, *Ca I* 4227, 4435, and 4456 are weak. Typical stars, θ *Scorpii* *gF*₀; η *Piscium* *gG*₅; α *Boötis*, *gK*₀ and β *Pegasi*, *gM*₃.

(5) The prefix *d* should be used for faint dwarf stars of Class F₀ or later. The lines above-mentioned show reversed relative intensity to that of the giant stars; low temperature lines, including *Ti* 4535, weak in the giants, show up as strong for the dwarfs and vice versa. In Class F *Sr II* 4077, 4216, and *Ti II* 4290 are weak. In Class M *Sr I* 4607 is strong. Typical stars, α *Canis Minoris*, *dF*₅; μ *Herculis*, *dG*₅; 70 *Ophiuchi* (Br.), *dK*₀, and *Lal.* 21185, *dM*₃.

(6) It is recommended that standard or typical spectra should be chosen from among the giant stars, preferably of absolute magnitude about 0 or 1 (except for Class B, where they must necessarily be brighter). This would involve such substitutions as ν *Persei* for α *Canis Minoris* in Class F₅.

(7) Spectra showing all lines unusually wide or diffuse should have the affix "n," and those showing sharp lines without the c-characteristics should have the affix "s." For instance α *Leonis* would be B8n. The letters "n" and "s" qualify the preceding symbol.

(8) The symbol "k" is proposed for stars with special stationary lines, such as [H] and [K] and the [D] lines. Typical star, δ *Orionis*, Bonk.

(9) Bright lines should be denoted by the letter "e,"* except in classes whose definition involves the presence of bright lines. Cases where the bright lines are conspicuously

* This is the reason for replacing class Md by the class Me, subdivided according to the nature of the absorption spectrum into subclasses M1e, M2e, etc.

reversed with a dark centre would be denoted by "er," while, if the bright lines are bounded on the violet side by absorption lines, the letters "eq" are suggested. It is also suggested that where some of the hydrogen series—starting from the red end—are bright, the letter α , β , etc., should be added, to indicate which is the last visible bright line. Typical stars, γ Cassiopeiæ, Boe; P Cygni, B4eq; and α Cygni, cA2ea.

(10) The letter "p" is reserved for miscellaneous peculiarities, and it should be used to qualify the symbol immediately preceding. The same rule should apply to the symbols "n" and "s."

The final notation for the spectra of gaseous nebulæ has not been settled, but it is important to distinguish where possible between the spectra of the nucleus and of the surrounding envelope.

The letter Q is suggested for novæ, with a series of letters to indicate the presence of certain simple types of spectrum or types of associated spectra. Here, again, the final details are not yet worked out. It should be pointed out once more that the Draper classification of § 54 suffices for ordinary use, and that the modifications and additions of the present paragraph will chiefly be of use in special technical investigations. They do, however, offer a means of conveying, in brief compass, very useful additional information as to a star's spectrum.

CHAPTER IX

GIANT AND DWARF STARS

56. The Single Line of Evolution.—At the end of the nineteenth century, and for the first decade of the twentieth century it was fairly generally believed by astronomers, with a few notable dissentients, that the sequence of spectral classes followed above, namely P — O — B — A — F — G — K — M (or G — R — N), represented the normal line of development of the stars from planetary nebulae. The words “early” and “late” applied to this sequence also applied to a star’s position in the evolutionary time-scale. In favour of this view were facts of the following nature. There is a complete sequence of spectra from the gaseous nebulae to the red stars, and the great majority of the stars can be placed at some definite point in the sequence. The sequence was made first of all from the appearance of the spectra, but laboratory experiments showed that it corresponded to a gradually changing physical condition, which has been interpreted in terms of temperature or ionization. The sequence appeared to represent an order of progressively lower temperature or decreasing ionization for the stellar atmospheres. A single line of development was similarly indicated by Campbell’s result* that the radial velocities of stars changed steadily along the sequence of the above scheme. The only exceptions were the planetary nebulae which came at the wrong

* “Stellar Motions,” p. 207, 1913; see also § 46 above.

end of Campbell's table. (We now know that Class Oe stars are also exceptions.)

Still further evidence *pointing to the same order of development was supplied by Campbell * from a study of the periods of spectroscopic binary stars. Two-thirds of the binaries of Classes O and B that he examined had periods less than 10 days; half the Class A and half the Class F binaries had periods less than 10 days; no known binaries of Classes G, K, M (with one possible exception) had periods of less than 20 days. All this evidence suggested the same single line of development. So, also, did the distribution of the stars in the sky. "Early" stars are concentrated in the galaxy, and there is a tendency for stars of "later" type to diverge more and more from the galaxy. Altogether a very considerable body of consistent evidence had been brought together, all pointing to the same simple line of evolution, the chief outstanding difficulty lying in the early stages of the scheme, the direct transformation from the original nebulæ to the hottest stellar types.

57. The Two-Branch Theory of Evolution.—On the theoretical side Ritter,† following Homer Lane,‡ and on the observational side Sir Norman Lockyer,§ steadily maintained that it was essential that any evolution scheme must provide for a branch of ascending temperature as well as for a branch of descending temperatures. Instead of one single line of development from the hot stars of Class O down to the red stars, this alternative scheme starts with an extended mass of gas at low temperature and allows for an increase of temperature as the gas contracts—it is, in fact, a scale of *increasing density*, and stars of a given

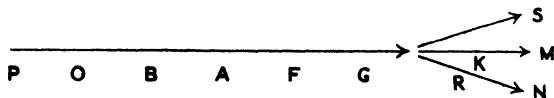
* "Stellar Motions," p. 261.

† *Annalen der Physik*; eighteen papers in vols. v.-xx, 1878-83.

‡ *American Journal of Science*, 1. 57, 1870.

§ *Proc. R.S.*, lxxv. A, 188, 1899; lxxiii. A, 227, 1904; lxxvi. A, 145,

spectral type may belong either to the branch of increasing temperature or to the branch of decreasing temperature. The scheme is no longer to be represented as



but as

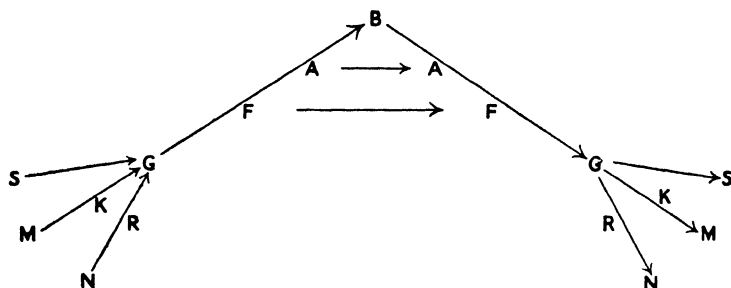


FIG. 4.

The course of evolution sketched by Ritter starts with a widely extended nebulous mass of gas of very slight mean density. With loss of heat by radiation the mass contracts and a slow increase of density is accompanied by a rise in temperature. As the density increases, the heat from the centre escapes less readily by radiation and we reach a culmination of light intensity at which the effectively radiating layer is only a small fraction in depth of the whole radius of the star. The quantity of heat radiated per unit area now diminishes, although the surface temperature increases for a time, the maximum of radiation shifting slightly to the violet. After the second culmination, that of maximum temperature, has been reached, both the total radiation and the surface temperature diminish rapidly, the star ceasing to obey the gas-laws owing to increasing density.

Several difficulties prevented the general acceptance of the views of Ritter and Lockyer. For one thing, evidence

had been steadily accumulating (as explained in § 56 above) which pointed to physical changes accompanying a single sequence of spectra. Again, not sufficient differences were recognized among stars of the same spectral class to justify the view that they formed two groups differing so much in density and pressure as was required by Ritter's theory. (In this Lockyer dissented from the views generally held.) Further, the spectroscopic link recognized as existing between the planetary nebulæ and the hot O and B stars was lacking between the nebulæ and the cool red stars. There was no evidence connecting nebulæ with the giant red stars of the branch of ascending temperatures. To some extent these difficulties have since been removed. For instance Merrill has found * in the spectrum of R Aquarii, a red variable star of type Md, the bright lines at 4363, 4658, 4959, 5007 which are typical of nebular spectra, as also, the helium line 4471 which occurs in nebulæ. Slipher at Flagstaff Observatory, has photographed this star, and finds it † to be surrounded by a nebulous envelope. Here, then, is one definite link between a red variable star and a nebulous mass of gas and, though too much stress must not be placed on one case, the objection that *no* link between the nebulæ and red stars has been found, has vanished. Again, Adams, in his work on spectroscopic parallaxes has definitely established detailed differences ‡ in the spectra of the stars of high and low luminosity—the giants and dwarfs—of the same spectral type. And Russell, Hertzsprung, and others, have collected a mass of explicit evidence which shows that for the later type stars we do get the same general spectrum accompanying stars of widely different luminosity and density; we do find the two groups of red stars required by Ritter and Lockyer.

58. Giants and Dwarfs.—As observational data increased

* *Ap. J.*, liii. 375, 1921. † *Observatory*, xlv. 100, 1922.

‡ See § 60 below.

it was found that by whatever criterion stars were examined in the separate spectral classes, the late type stars fell into two very different groups (Plate 25). Thus Hertzsprung,* from a study of proper motions, found that the red stars formed two groups of very different luminosity, which were subsequently called "giant" and "dwarf" stars. Russell, from a study of parallaxes,† confirmed this differentiation, and supported the suggestion that the essential difference lay in density and in surface area. We have already seen (§ 36 above) that late type stars have colour indices which separate out into two well-defined groups. For a given spectral type, the giants are redder or have lower effective temperatures than the dwarfs, or we may say that for a given temperature the giants are of earlier spectral type than the dwarfs. This is because the spectral type, defined by the relative strengths of different absorption lines, depends on the degree of ionization in the absorbing layer of the star's atmosphere, and this depends only partly upon the temperature, but partly, also, upon the gravitation at this layer.‡ Theory and observation agree as to the direction in which the difference of colour-index between the two classes should occur. Again, a study of the absolute magnitudes and spectra of double stars of known orbits gave clear evidence of the separation of giant and dwarf stars among the later spectral types and enabled Russell to tie the great difference in brightness definitely to a difference of superficial area rather than of mass;§ and the fact that for giant binaries the fainter star—generally the less massive one—is usually of earlier type, while for dwarfs it is usually of later type,|| is consistent with Russell's

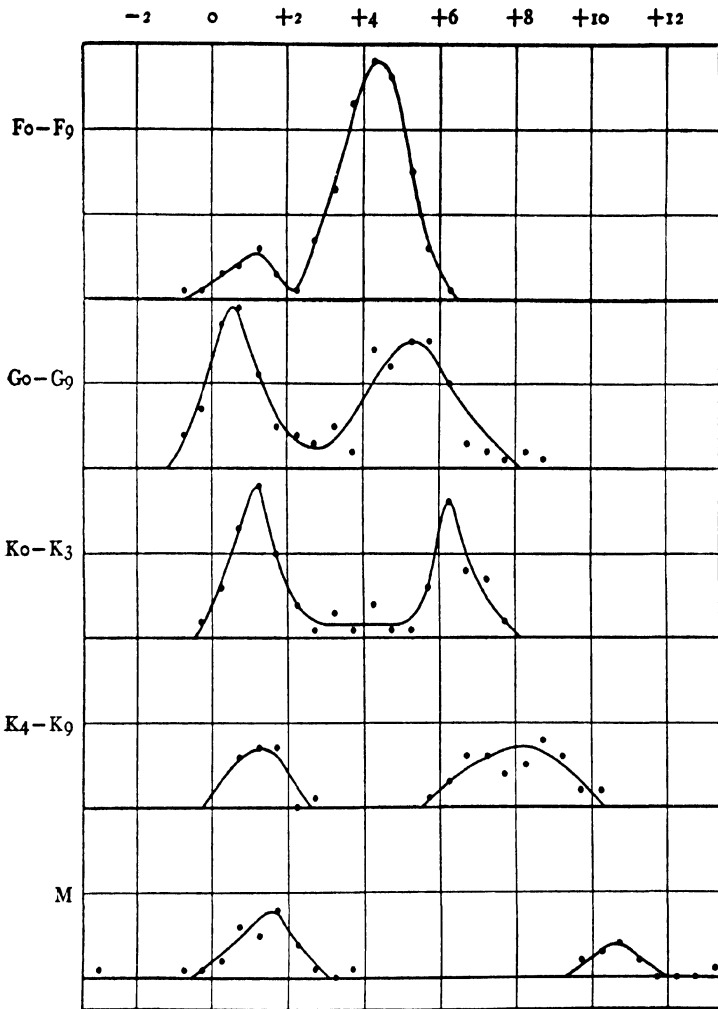
* *Zeit. f. Wiss. Photographie*, iii. 429, 1905, and v. 86, 1906.

† *A.J.*, xxvi. 147, 1910.

‡ Pannekoek, *B.A.N.*, No. 19, 115, 1922; R. H. Fowler and Milne, *M.N.R.A.S.*, lxxxiv. 508, 1924.

§ *Observatory*, xxxvi. 328, 1913.

|| Leonard, *Lick Obs. Bull.*, No. 343, 188, 1923.



FREQUENCY-CURVES OF ABSOLUTE MAGNITUDES FOR DIFFERENT SPECTRAL TYPES. ADAMS'S STUDY OF SPECTROSCOPIC PARALLAXES, 1917

theory, under the simple assumption that the less massive star passes through its development more rapidly than its more massive companion. We have seen (§ 39 above) that there are very good reasons for believing that the masses of stars all fall within a fairly narrow range; it is density and superficial area that vary greatly rather than mass. But, as we have seen, the mass of a star in radiative equilibrium is a controlling factor in determining its temperature and spectrum. In Russell's theory, as first stated, the temperature determined by a star's mass might be taken to be the highest temperature reached by the star in its evolution up the branch of ascending temperature. Only the most massive stars would reach the B Class, others moving across from the branch of ascending temperature to the descending branch at Classes A, F, and so on, according to their masses; the less massive stars would change over at lower temperatures than the more massive stars. (Stars of less mass than one-seventh the sun's mass would never rise to a temperature at which they would become visible to us.)

59. Mass and Evolution.—It is on the close connection between a star's mass and its luminosity (and indirectly its spectrum) that the most recent speculations on stellar evolution depend. If we regard the course of evolution as so slow that the great bulk of the stars, even the dense dwarfs, may be considered as being in radiative equilibrium, then we must cease to regard the sequence of stellar spectra as necessarily representing successive stages in stellar evolution. Each star is in equilibrium and has the absolute magnitude and spectrum appropriate to its own mass. We have no knowledge of the stages through which it passed before it reached stability, we have no clear view of the future stages through which it has yet to pass. Only when we assume that the fundamental variant, the mass of a star changes in some definite way, can we once more sketch out

a scheme of stellar evolution. Recent speculation has examined this point too.

We are no longer content with Kelvin's view that the sun's radiant energy is supplied by the loss of gravitational energy consequent upon contraction. Contraction is not capable of supplying anything like sufficient energy to suit the time-scale of the modern cosmogonist or of the geologist. Some fresh source of energy must be found to supply the outgoing radiation, and modern theory has found this in the connection between mass and radiant energy. The theory of relativity has shown that, if energy dE escapes from a body as radiation, the mass of the body must diminish by dE/c^2 where c is the velocity of light. Thus energy of radiation is obtained from the actual annihilation of matter, by the destruction of electrons and protons. We come back to the idea that the star is burning itself away, radiant energy replacing mass.

The old single line of evolution, or the branch of decreasing luminosity in the two-branch theory of evolution, will fit into the new order of ideas quite satisfactorily, the only change being to replace increasing density by decreasing mass as the main evolutionary factor. It is not so easy, however, to determine the position and fate of the giant stars of low temperature. Until we have had further knowledge of the connection between a star's mass, the rate of generation of sub-atomic energy and the resulting internal and effective temperatures, it is idle to speculate on the course which such a star will follow. Statistical considerations suggest that the red giant follows along the sequence of ascending temperature of the two-branch theory, its temperature increasing while its luminosity decreases; this fits in with Coblentz's estimate* that the average absolute luminosity of the red giants is greater than that

* *Scientific Papers of the Bureau of Standards, Washington*, No. 438, 1922. See also a table and figure by Danjon, *L'Astronomie*, xxxv. 425, 427, 1921.

of the yellow giants, but it is inconsistent with Adams's result that at the other end of the sequence, for A and B stars, the earlier types are the more luminous. More data on the statistical distribution of the masses and temperatures of giant stars must, however, become available before we can place the branch of ascending temperatures once more in a secure position as part of the scheme of stellar evolution. One curious point will even then await explanation and that is the nature of the mechanism which nearly equates the rate of production of sub-atomic energy in the interior of a star to the rate of outflow of radiation. How do these two disparate quantities so nearly balance as to leave the star apparently in a stable condition, subject only to a very gradual secular change?

60. Spectroscopic Parallaxes.—The study of giants and dwarfs leads naturally to an examination of the minor differences between the stars of similar spectral type which differ markedly in luminosity. Russell first showed that a relationship existed between a star's luminosity and its spectrum. In the skilful hands of Adams at Mount Wilson,* this relationship led to the determination of stellar distances from a study of stellar spectra. Having used the relative intensity of hydrogen and iron lines for an accurate classification of stellar spectra—the Harvard scheme was adopted with careful grading between classes—a careful study was made of two stars of the same spectral class and of known parallax, which differed considerably in luminosity. Thus *α Tauri* (K5) and *61¹ Cygni* (K7) have absolute magnitudes 0.4, 8.0 respectively, or the former is 1100 times as luminous as the latter. Adams found that low temperature lines, such as *Ca I 4435* were stronger in *61¹ Cygni*, while enhanced spark lines, such as *Sr II 4216*, were stronger in *α Tauri*. The varying behaviour of these two lines for stars of high

* *Ap. J.*, xl. 385, 1914; xlvi. 313, 1917; liii. 13, 1921. *Proc. N.A.S.*, ii. 143, 1916.

and low luminosity was found to persist through a wide range of spectral types. With the aid of a number of stars of known parallaxes and magnitudes, numerical relations were established between the absolute magnitudes of the stars and the difference in the intensity between the pair of lines considered (Plate 26). When the difference of intensity was plotted against the absolute magnitude the graph came out as a straight line for stars of spectral types Fo to K4—thus the difference of intensity of the selected pair of lines was a linear function of the absolute magnitude.

We need not follow in detail the various steps by which Adams extended, checked, and made good his method of determining absolute stellar magnitudes from a study of spectra. It will be enough here to mention the lines he finally adopted as keys to stellar luminosity and the deductions as to giant and dwarf stars.

For the range of spectrum Fo-F5 the pairs chosen were:

Lines Strong in Stars of Low Luminosity.	Lines Strong in Stars of High Luminosity.
<i>Fe</i> I 4072	<i>Sr</i> II 4077
<i>Fe</i> I 4250	<i>Sr</i> II 4216
<i>Fe</i> I 4271	<i>Ti</i> II 4290

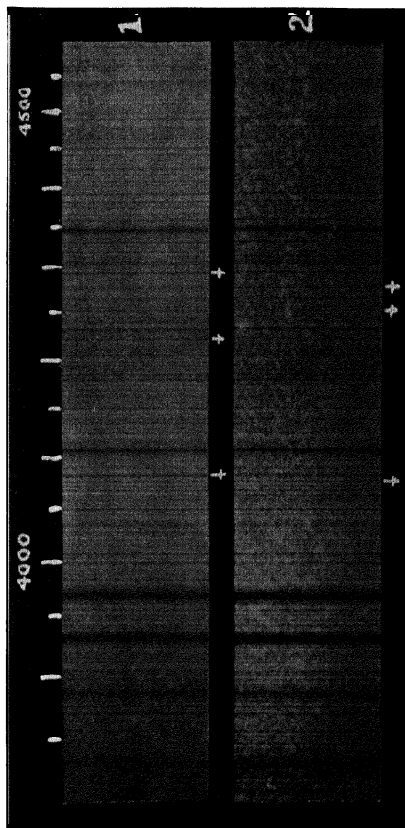
For the range F5-K8:

<i>Fe</i> I 4250	<i>Sr</i> II 4216
<i>Ca</i> I 4456	<i>Fe</i> I 4462
<i>Ca</i> I 4456	<i>Fe</i> I 4495

For the range K8-M:

<i>Ca</i> I 4456	<i>Sr</i> II 4077
	H δ
	<i>Fe, V</i> I 4207
<i>Sr</i> I 4607	<i>Sr</i> II 4216
	H γ

The accompanying figure (Plate 25) shows plainly how Adams's criteria divide the later type stars clearly into two



I. v PERSEI—GIANT
 2. a CANIS MINORIS—DWARF } SPECTRUM F5

Spectrograms taken at the Norman Lockyer Observatory. The lines strengthened in each star are indicated by +

classes, the giants and the dwarfs. The work of Adams finally disposes of the objection that stars of very different physical condition could not show spectra fundamentally alike and differing only in small details. Adams's earlier work has been followed by investigations at other observatories. Fresh pairs of comparison lines for stars of high and low luminosity of types Fo to Mb have been taken into use.* Further, an extension has now been made to include in the scheme the hotter stars of Types A and B. Thus Adams and Joy † have found that among A type stars those with sharp and narrow lines are more luminous than those of the same spectral type with diffuse lines. They also found that the average luminosity of the stars increased steadily from absolute magnitude 2.6 at A9 to 1.0 at A.0 (diffuse lines). Both these results have been confirmed by G. Abetti. ‡ The steady increase in luminosity continues through the B type spectra, the average absolute magnitude for B0 (diffuse) being -3.1 . § Edwards, || by a method more in accord with Adams's earlier work, showed that for B stars the absolute magnitude could be determined by the relative intensities of certain lines of helium and hydrogen, the helium being relatively weaker for the stars of greater luminosity. This result seems inconsistent with the fact that *He I* lines are at maximum strength at Class B2, while the *H* lines are at maximum at A0. The apparent anomaly is, in large part, due to the fact that the relative strength of some *He I* lines and the *H* lines are taken into account

* Rimmer, *Memoirs R.A.S.*, lxii. 113, 1923, lxv. 1, 1925; *H.C.O. Circ.*, 228, 1921; 232, 1922; 243, 1923; Young and Harper, *Journal R.A.S., Canada*, xviii. 9, 1924; *Pub. D.A.O.*, iii. 1, 1924.

† *Proc. N.A.S.*, viii. 173, 1922, and *Ap. J.*, lvi. 242, 1922.

‡ *Pubb. del. R. Inst. di Studi Sup. in Firenze, Fascicolo No. 41*, 1924.

§ *Pub. A.S.P.*, xxxv. 120, 1923, and *Ap. J.*, lvii. 294, 1923.

|| *M.N.R.A.S.*, lxxxiii. 47, 1922.

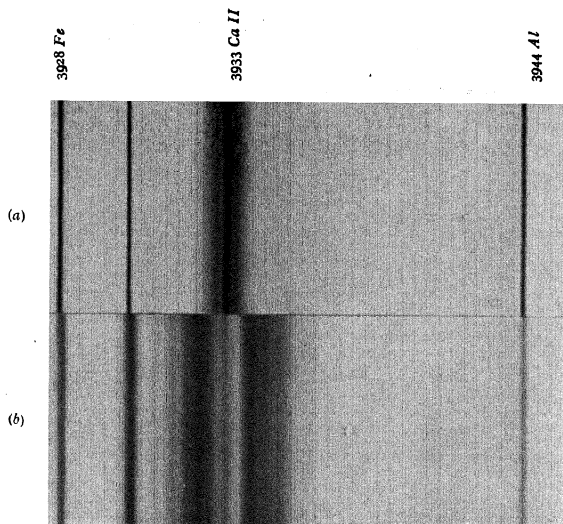
in classifying the star. What is measured by Edwards is a secondary effect.

Deslandres * and Burson have suggested a further spectral difference between giant and dwarf stars. They have found evidence for bright chromospheric lines [H_2] and [K_2] in the upper atmospheres of several giant stars of types G, K, and M (Plate 27). For these stars they have found that the bright lines are broader with increasing luminosity and much broader in the case of the giant stars than in the case of the sun, a dwarf. Here we may find ultimately a valuable clue in our analysis of the differences between the spectra and the density gradients of the atmospheres of giant and dwarf stars.

It is, perhaps, worth repeating here that, what the difference in the spectra measures directly is not the absolute luminosity (L) of the star, but really the gravitation at its surface. It is this which mainly affects the degree of ionization in the atmosphere for a given temperature.† It is because $g \propto \sigma M/L$, where σ , the surface brightness, is constant for a given class, while M , the mass, varies only slightly compared with the enormous accompanying changes in L , that we get so good a measure of a star's absolute luminosity from a study of its spectrum.

* *C.R.*, clxxv. 121, 1922.

† Pannekoek, *B.A.N.*, No. 19, 115, 1922.

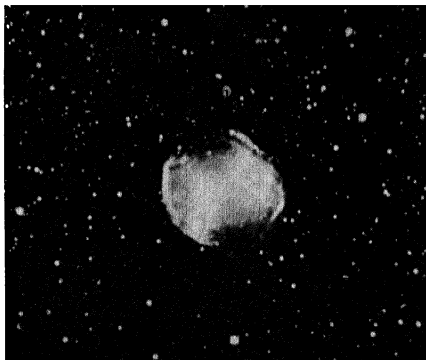


(a) SPECTRUM OF THE SUN WITH A HIGH DISPERSION TO SHOW $[K_2]$, $[K_3]$

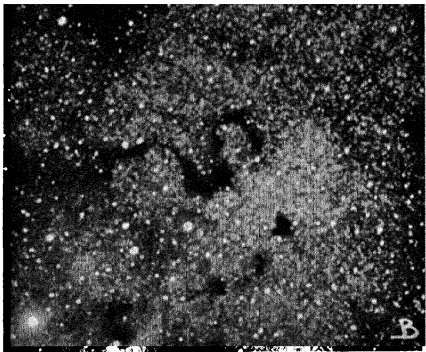
(b) SPECTRUM OF ARCTURUS, A GIANT STAR OF CLASS K0, SHOWING $[K_2]$, $[K_3]$

Spectrograms were secured at Meudon by H. Deslandres. In the original spectrum of Arcturus the distance from $[H]$ to $[K]$ is 4 mm. The dispersion in the case of the solar spectrum was 5 times as great. Both spectrograms are given here reduced the same scale

(a)



(b)



(a) THE "DUMBBELL NEBULA"

Photographed with the 2-ft. reflector of the Yerkes Observatory

(b) DARK MARKING NEAR θ OPHIUCHI, $\alpha = 17$ H. 16 M. 17
 $\delta = -23^{\circ} 37'$

Photographed by Barnard with the Bruce telescope at the Yerkes Observatory

CHAPTER X

NEBULÆ

61. Main Types.—There are to be found many masses in the sky consisting of a glowing gas of unknown nature ; these often show a stellar nucleus and may represent the pre-natal condition of a star. As already stated, the evidence for a link between these nebulous masses and the red giant stars is limited to the case of R Aquarii, a red variable star surrounded by a gaseous envelope which shows bright nebular lines in its spectrum. These bright line nebulæ, very varied in appearance but with fairly defined boundaries, are called *planetary nebulæ* (Plate 28). To study the many curious forms found, the reader is referred to the magnificent volume on nebulæ recently published by the Lick Observatory—*Publications of the Lick Observatory*, vol. xiii.

Diffuse in appearance and thoroughly irregular in shape come the *diffuse irregular nebulæ*. Some of these are shown by the bright lines in their spectra to consist of the same type of gas as is found in the planetary nebulæ, though the matter is here not condensed round central nuclei. For other diffuse nebulæ the spectrum is continuous with absorption lines. There is some relation * connecting the spectrum of a diffuse nebula and those of the stars which seem to be most clearly associated with or involved in it. The nebulæ with bright line spectra are connected with stars of earlier type than the stars connected with nebulæ with absorption

* Hubble, *Ap. J.*, lvi. 162, 400, 1922.

spectra. Though these nebulae do not shine with reflected light from the stars it looks as though their luminosity was excited by light from the star. The sequence runs from a planetary nebula excited by a hot Wolf-Rayet stellar nucleus, through a diffuse nebula with continuous spectrum excited by B type stars, down to an opaque or dark nebula which has not been excited to luminosity.

There are known in the sky many dark lanes and patches which may be *dark nebulae* (Plate 28), perhaps irregular nebulae which have not yet reached, or have passed, the physical condition in which they become visible. Barnard * made a special study of these dark markings and gave very good grounds for the view that they consist of dark screening matter between us and the background of stars rather than that they are mere gaps in the grouping of the stars as seen from the earth.

The planetary nebulae are concentrated near the galaxy. The most important class of nebulae, the *spiral nebulae*, show a marked aversion to the plane of the galaxy. These nebulae will be discussed below. Here we must mention that the spectra of these nebulae are generally absorption spectra, frequently of solar type. The integrated spectrum of the Milky Way † is of the same nature, a fact which lends support to the suggestion that the spiral nebulae are very distant aggregations of stars, like the Milky Way. Some of these spiral nebulae also show bright nebular lines in their spectra.‡ These may come from the presence in the spiral nebulae of enormous patches of bright nebulosity, such as we find in the Magellanic Clouds. Reynolds § has suggested that the light of spiral nebulae is due to reflected light from a central star or nucleus. This suggestion applies mainly

* *Ap. J.*, *passim*, in particular, xlix. 1, 1919.

† Fath, *ibid.*, xxxvi. 362, 1912.

‡ Fath, *ibid.*, xxxiii. 59, 1911.

§ *M.N.R.A.S.*, lxxii. 553, 1912.

to nebulæ whose condensation into separate stellar masses has not proceeded too far, and it should be considered in connection with Hubble's suggestion of the excitation of light in diffuse nebulosity by stellar sources of intense radiation.

The Clouds of Magellan, with some hundreds of nebulous objects and star clusters, resemble the Milky Way in many respects. They offer the only part of the sky outside the galactic regions where stars and nebulosities with bright line spectra are found in profusion. The clouds, both by reason of their appearance, and also by reason of the high radial velocities—averaging $+ 276$ km./sec.*—of the nebulæ which lie in them and move with them should probably be classed with the spiral nebulæ.

62. Radial Velocities.—We have already seen (Table V above) that the planetary nebulæ have a large average radial velocity, a fact that would place them near the dwarfs rather than near the giants in the evolution scale. The average radial velocity for 31 stellar planetary nebulæ after allowing for the solar motion relative to the brighter stars, is 28 km./sec., the average for 65 non-stellar planetary nebulæ is 31 km./sec.,† while the average for the Class B stars is only 6 km./sec. There is obvious difficulty in regarding the planetary nebulæ as the direct forerunners of the main body of the Class B stars, especially when we realize how few of the former are known—about 125 in all (but see Chapter XIV below). But planetary nebulæ share the high radial velocities with Class O stars. These two classes of bodies do seem to be organically related. The average radial velocity of the diffuse gaseous nebulæ is only 11 km./sec., which seems to differentiate them from the planetary nebulæ on the one hand and from the spiral nebulæ on the other. These nebulæ may be

* *Lick Obs. Pub.*, xiii 189, 1918.

† *Ibid.*, 173, 1918.

related to the stars of Class B. V. M. Slipher has found * an average radial velocity of approximately 600 km./sec. for 41 of the spiral nebulae, the highest velocity observed being + 1800 km./sec. The great majority of these velocities are positive, indicating a general recession of spiral nebulae from the sun or rather from the galaxy, if the displacement of the spectral lines is to be ascribed to velocity alone.

Attempts have been made to explain the recession of the spiral nebulae in several ways. De Sitter,† in accordance with his theory of relativity, has explained the displacement of the spectral lines to the red as being due, in part, to a general tendency for particles to scatter and in part to the slowing down of atomic vibrations of distant objects. Lindemann would account for the recession of the spiral nebulae as being due to light pressure from our galaxy, the nebulae being, in his view, clouds of dust shining by reflected light from the galaxy.‡ Neither explanation can be accepted as satisfactory, and the large displacements of the spectral lines in the spiral nebulae remain a perplexing and unsolved problem.

63. Internal Motions in Gaseous Nebulae.—Campbell and Moore, in their study of the spectra of the bright line nebulae, have investigated the evidence for internal motions. For more than half the objects examined, the spectral lines have indicated internal motions in the nebulae. For many of these cases the simplest interpretation appears to be that the nebulae are rotating about axes approximately perpendicular to the line of sight, the highest rotational speeds being found for the most elongated planetary nebulae. In addition, a certain number of planetary nebulae, mainly those which show the ionized helium spectrum, have the principal nebular lines doubled over their central portions. This

* Eddington, "The Mathematical Theory of Relativity," p. 162, 1923.

† *M.N.R.A.S.*, lxxviii. 28, 1917.

‡ *Ibid.*, lxxxiii. 354, 1923.

doubling may be due to a reversal of a broad bright line by outer layers of cooler gas, it may be due to a central expansion or contraction of the nebula as a whole (velocities of the order of 30 km./sec. are indicated), or, again, it may be in some way, of atomic or sub-atomic origin. On the whole, one of the first two explanations is the most likely. In addition to the doubling of nebular lines found by Campbell, Slipher and Sanford have shown that certain nebulae have lines doubled to an extent that would require much higher internal velocities, namely, of the order of 500 km./sec. if the doubling is to be explained in terms of velocities. In confirmation of this explanation comes the announcement by Slipher that photographs of the Crab Nebula give evidence of internal movement, relative displacements of well-marked nuclei having been measured.* The subject is ripe for further investigation.

64. The Distances of the Spiral Nebulae.—In a recent series of papers † van Maanen has compared recent photographs of some of the larger spirals with earlier photographs, and has studied the motions of definite condensations in the arms relative to the stellar background. As Jeans foretold on theoretical grounds,‡ the motions discovered are outward along the arms of the spiral, the velocities generally increasing with distance from the centre. The hypothesis of outward motion along the arms agrees better with the observations than the hypothesis of simple rotation of the nebula as a whole. It has this difficulty, however. The time taken for matter to do one complete circuit round the nucleus is on the average less than 100,000 years and the two arms of the spiral show too few convolutions for the nebula to be more than several hundred thousand years old. In terms of the time-scale now generally adopted for the sidereal

* *Observatory*, xlii. 322, 1919; xliv. 160, 1921.

† See, among others, *Ap. J.*, xlv. 210, 1916; lvii. 264, 1923.

‡ *Observatory*, xl. 60, 1917.

universe, this makes spiral nebulæ as a class improbably young and we are driven to the view that the arms of nebulæ disperse into stars accompanied, probably, by a great mass of invisible dark matter. There is not a great deal of evidence for dark matter surrounding such spiral nebulæ as are so placed that we see the spirals openly and well (Plate 29). In this case, however, the presence of bright condensations surviving along with the dark matter might disguise the phenomenon. For spiral nebulæ placed edge on to us there is a considerable body of evidence as to occulting matter in the outer regions.* In fact, the presence of such matter seems to be the rule rather than the exception. And this together with the presence of dark lanes between the bright whirls of the spiral nebulæ seems to fit in with the views as to their evolution developed by Jeans. According to one view, the spiral nebulæ are at enormous distances, and may be regarded as of the same size and nature as the galaxy. The size of the proper motions observed in them would mean such enormously high internal velocities that any comparison with the galaxy would be out of the question. The idea of spiral nebulæ as island universes, offered first by the elder Herschel and revived periodically by later investigators, seemed to have received a very heavy blow in this work of van Maanen. More recently, Hubble from a study of the light-curves of 12 Cepheid variables in the Andromeda nebula has derived for it the enormous distance of 950,000 light-years.† Hubble's results would give impossibly high values for the velocities of the nuclei determined by van Maanen, and it would appear that these motions are illusory. The theory of the island universe has been restored to favour once more.

65. The Nebular Spectrum.—The first spectroscopic examination of a nebula was made by Huggins in 1864, when he turned his telescope on the planetary nebula in Draco.

* See *Lick Obs. Pub.*, xiii. Plate III.

† *Popular Astronomy*, xxxiii. 143, 252, 1925.



MESSIER 101

Photographed with the 24-inch reflector of the Yerkes Observatory

His own account * is worth repeating, if only for the spirit that it reveals :—

“ I looked into the spectroscope. No spectrum such as I expected ! A single bright line only ! At first I suspected some displacement of the prism and that I was looking at a reflection of the illuminated slit from one of its faces. This thought was scarcely more than momentary ; then the true interpretation flashed upon me. The light of the nebula was monochromatic . . . a little closer looking showed two other bright lines towards the blue. . . . The riddle of the nebulae was solved. The answer which had come to us in the light, itself, read : not an aggregation of stars, but a luminous gas.”

This discovery came at an opportune moment when the resolutions of so many nebulae into clusters of stars by Lord Rosse's great telescope had led to the idea that all nebulae were mere close aggregations of stars. The work of Keeler at the Lick Observatory, and later of W. H. Wright at the same observatory, has given us a nebular spectrum with many more lines than the three seen by Huggins. These three were the two principal nebular lines [N_1] and [N_2], at 5007·02 and 4959·09 respectively, together with the hydrogen line $H\beta$.

The bright lines found in nebular spectra include the Balmer series of hydrogen, lines of ionized helium, nitrogen and carbon, familiar in the stars of Classes O and B, and, in addition, a number of lines of unknown origin due, perhaps, to some unknown element. At least two elements seem to be involved. Nicholson † found that he could tie together the wave-lengths of most of the lines in terms of the periods of vibration of a model atom with nucleus $+4e$, and with one ring of 4 electrons for the neutral atom. The accuracy of

* “ Scientific Papers of Sir William Huggins,” vol. ii. 106, 1909.

† *M.N.R.A.S.*, lxxii. 49, 1911, and see § 22 above for similar work on the coronal spectrum.

fit of spectrum to model is not as close as in the case of the coronal spectrum, but there is good agreement save for a few outstanding lines. One of the lines originally left out of his scheme by Nicholson was the ionized helium line at 4685·7, which was subsequently discovered in the laboratory by Fowler in 1912.* Other lines outstanding from Nicholson's scheme were the lines 3726, 3729, for which Buisson, Fabry, and Bourget later claimed a different origin from that of the line 5007·0. Their method depended on measuring the widths of the lines of the spectrum. Assuming the widths to be due to the velocities of the atoms of the gas—a somewhat rash assumption, as we know now—it was possible by the kinetic theory of gases to deduce the temperature of the nebula and the atomic weights of the gases concerned. The temperature of the Orion nebula came out at 15,000°, and the atomic weight of the gas giving the doublet at 3727 came out at about 3, and that of the gas giving the line 5007·0, came out somewhat lower.† That the doublet at 3727 differs in some very significant way from the principal nebular line has been strikingly demonstrated by Wright.‡ (Plate 30.) The distribution in certain nebulae of the gas giving this doublet is very different from that of the gas giving the principal nebular line. The presence of two elements, or of one element in two distinct physical conditions, is indicated.

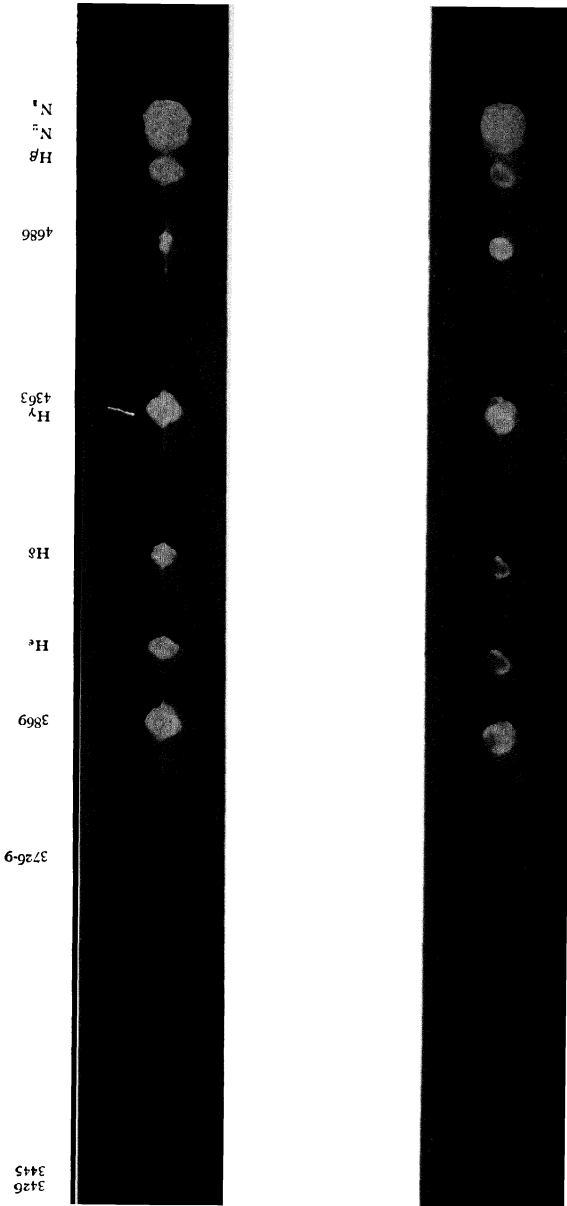
The best table of the wave-lengths of the spectral lines found in the nebulae is given by Wright.§ The lines vary in relative strength from nebula to nebula, especially when compared with the hydrogen and helium lines. These

* The line had been seen on some laboratory plates taken at South Kensington in 1898 (*Proc. R.S.*, lxxiv. A, 545, 1905). † It was first isolated in a helium vacuum tube by Butler in 1909.

‡ *Ap. J.*, xl. 257, 1914.

§ *Lick Obs. Pub.*, xiii. Plates XLVIII, L.

§ *Ibid.*, Table II, and see Appendix VIII below for the chief lines.



variations in intensity have been adopted as the test for use in classifying the spectra of the nebulæ. But, before this classification is discussed, mention must be made of one very significant fact. The nuclei of many planetary nebulæ show the spectra of Wolf-Rayet or Class O stars, while the outer envelopes have the more typical nebular spectrum. Thus, at the other end of the temperature scale from R Aquarii we have frequent illustrations of stars with nebular envelopes. There is, however, just this difference between the two cases. The evidence points to planetary nebulæ with stellar discs as expanding, whereas nebulosity connected with red giant stars is generally assumed to be contracting.

The extension of the continuous spectrum of the nuclei of planetary nebulæ into the extreme ultra-violet also calls for mention.* It is not impossible that this extension of the continuous spectrum is due to high thermal excitation and may indicate a temperature higher than that found for any ordinary stars; it is more probable, however, in view of a similar phenomenon in the spectrum of the prominences and a connection between one edge of this continuous spectrum and the limit of the Balmer series, that the spectrum is due to hydrogen, in some condition of excitation not yet repeated in the laboratory.

66. Spectral Classification.—It is not possible as yet to lay down with any confidence the order of evolution, if any, connecting (a) Class O stars having no nebulous envelope; (b) planetary nebulæ with Class O nuclei; and (c) planetary nebulæ without nuclei. The older views on stellar evolution would undoubtedly make the order (c), (b), (a) leading on to the Class B stars. The more recent views do not include the planetary nebulæ in their general scheme of evolution. Possibly certain Class B stars, perhaps the most massive,

* See *Lick Obs. Pub.*, xiii. 256, 1918.

instead of developing along the line of descending temperature, rise still further in temperature into Class O ; then, some kind of instability sets in and nebulous matter is driven forth by some process which ultimately dissipates the whole stellar nucleus. That this is not the only possible line of development for planetary nebulae we shall see below in the chapters on novae and cosmogony. According to some writers, planetary nebulae are to be regarded as the wrecks of new stars which have, in the past, blazed suddenly up in the heavens.

The Draper classification (see § 54 above) depends mainly on the relative intensity of certain lines, notably 5007, 4959, 4686, 4363, 3729, and 3726. The difficulty of adopting this classification lies partly in the fact that different lines vary considerably in relative strength at different points in the same nebula. Wright suggests * in his investigation of the details of nebular structure, the following scheme :—

Class I, 4686 present in the *nebula*.

(a) 3426 stronger than 3445.

(b) 3445 stronger than 3426.

(c) Both 3426 and 3445 absent.

Class II, 4686 absent from the *nebula*, but 3869 present, with sub-classes according to the strength of 3869.

Class III, 4686 and 3869 both absent.

The shape and structure of the nebula and the relations of the nebular to the nuclear spectrum must also be taken into account. When the clue as to the formation and development of nebulae has been found, it is probable that shape and structure will be found to play a prominent part in any evolutionary classification.

* *Lick Obs. Pub.* xiii, 262, 1918.

CHAPTER XI

NOVÆ

67. Historical Novæ.—The earliest reference to a new or temporary star appearing in the sky is to be found in the Chinese records of Ma-tuan-lin.* The first star so recorded was in the year 134 B.C., and it is said by the elder Pliny † to have led Hipparchus to complete his star catalogue :—

“ Ideoque ausus rem etiam deo inprobam,
adnumerare posteris stellas ac sidera ad nomen expungere
organis excogitatis per quae singularum loca atque magni-
tudines signaret, ut facile discerni posset ex eo, non modo
an obirent ac nascerentur, sed an omnino aliquæ transirent
moverenturque, item an crescerent minuerenturque, caelo
in hereditate cunctis relicto, si quisquam qui cretionem eam
caperet inventus esset.”

The most famous new star in the pre-telescopic days was the star of 1572, which attracted back to astronomy the great Danish pioneer—Tycho Brahe. This star in the constellation Cassiopeia was said to be brighter than Sirius or Jupiter at its brightest ; it was seen in daytime and remained visible to the naked eye for fifteen months. With greater telescopic power available, with an increased number of observers watching the skies with accurate charts available for comparison, it is natural that the frequency of discovery of new stars should have increased. We may note that four new stars have been observed with the naked eye in the course of the present

* *Connaissance des Temps*, 1846, 61.

† *Naturalis Historia*, Bk. II, Ch. 26.

century. Nova Persei—in the accepted notation N Persei 1901—was discovered at Edinburgh by the Rev. T. D. Anderson at 14 h. 40 m. G.M.T., on 21st February; having already had the good fortune to find one nova—N Aurigæ 1892—this observer was on the look-out for another, and he secured his second find as the result of much faithful searching. At discovery, Nova Persei was of magnitude 2.7. Twenty-seven hours earlier, it was definitely fainter than 11.0 m.; thirty-eight hours after discovery it had reached a magnitude of 0.1. After this, it decreased in brightness, fairly rapidly at first, then more slowly, with a series of oscillations in brightness. The accompanying changes of spectral type will be discussed later. Nova Geminorum—N Geminorum 1912—was discovered by Enebo, at Dombaas, in Norway, when studying red variables in a special region of the sky. Its magnitude at discovery was 4.2, and the evidence from the Harvard photographs was that the star's brightness had increased by 6.5 magnitudes at least in the preceding twenty-three hours. The maximum reached was 3.4, after which the star slowly faded, again with marked fluctuations. Both the above stars have contributed to our knowledge of the spectra of novæ, but the star which promises to give the greatest amount of information on the origin and development of novæ is N Aquilæ 1918, discovered casually by many observers as of magnitude 0.8, on 8th June, 1918. This star had apparently been known for thirty years as a slightly variable star of about magnitude 10.5. In the course of four days it blazed up to a magnitude of -1 , becoming, for a short time, the brightest star in the northern sky. Its light curve followed much the same course as those of the two preceding stars. The last naked-eye nova, N Cygni 1920, was discovered by the veteran meteor observer, W. F. Denning, at Bristol, on 20th August, 1920, when at magnitude 3.5. This star increased more slowly than usual in the case of novæ to its maximum brightness,

1·8 m., but on the other hand it faded more rapidly and steadily after passing its maximum. In spectral development these four novæ followed the same general line of development as had been observed for N Aurigæ 1892. The later stars, however, gave far more detail, and the following paragraph is based mainly upon observations of them.

68. Spectral Development.—The study of recent novæ has given what appears to be the normal sequence of changes in the spectra of novæ. If observed early enough, while brightening, the star appears like an early A Class star (or a B Class star in the case of N Persei 1901) with the dark lines all displaced to the violet. The elements most strongly represented are generally hydrogen and ionized iron, titanium and calcium. The displacement varies as the wave-length and suggests motion of the absorbing gases towards the observer, the velocity of approach increasing or decreasing from day to day. The fact that the displacement always implies motion towards the observer is best explained by the fact that the absorbing gases form part of a jet, pulse, or shell of gas moving out from the centre of disturbance; when intervening between an observer and the star so as to show absorption lines on a bright continuous background, such outflowing gases must necessarily always be seen approaching the observer.

The second stage observed shows the presence of bright companions on the red side of the absorption lines. These bright companions rapidly broaden, and often show complex structure with several maxima. Their centres are approximately at the normal wave-length of the line identified with the absorption companion. When lines are crowded together in the spectrum the broad, bright bands are cut into by other dark lines, and the structure spoiled. Some of the lines, notably the hydrogen lines and a few of the enhanced metallic lines, next show a second dark companion which

is more displaced than the first, still in the direction of shorter wave-lengths. At this or some still later stage, these more displaced companions may be accompanied by dark lines corresponding to the carbon, oxygen, nitrogen, and helium lines prominent in Class B stars (Plate 31). We may have present in the same spectra an absorption spectrum of Class A, displaced by an amount corresponding to a velocity of -800 km./sec., and an absorption spectrum of Class B, displaced as by a velocity of -1800 km./sec.* In addition, there may be broad, bright bands present for one or both spectra and a further complication may be introduced by the presence of a spectrum of narrow, undisplaced absorption lines. The ionized calcium lines [H] and [K], and the ordinary [D] lines of sodium are commonly so found, and in the case of N Geminorum 1912 many ionized iron and titanium lines were also seen as undisplaced, narrow absorption lines on the bright bands of the spectrum.† At this stage the fading star is probably oscillating in brightness and in spectrum, the maxima corresponding to a stronger A Class spectrum and the minima to a stronger B Class spectrum. As the continuous spectrum fades away, and with it the A Class spectrum, a stage is reached where the star's spectrum appears to be almost wholly a bright band spectrum. Then we may have the following curious phases accompanying changes in stellar brightness: at light maxima—representing stronger continuous spectrum—we find strong absorption lines; at light minima strong, bright bands.

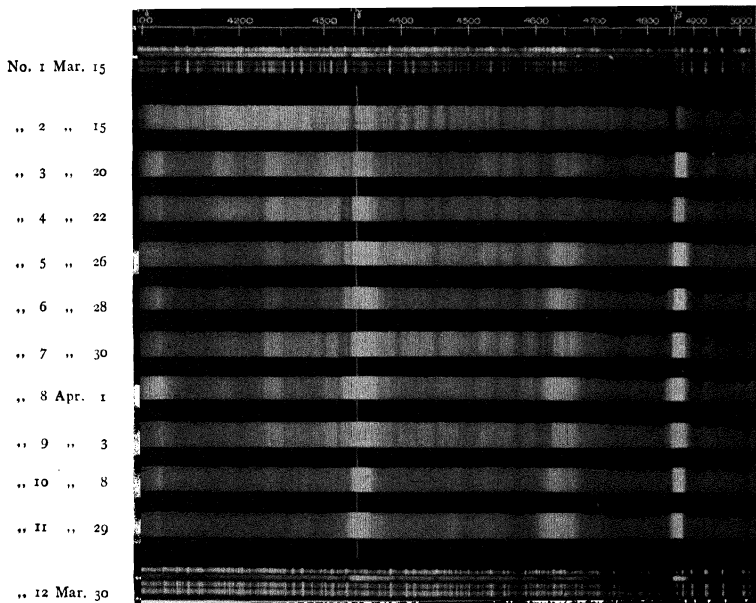
The bright metallic bands representing the Class A spectrum are the first to disappear and, as they go, they are replaced by broad, bright bands corresponding to the nebular lines. Fluctuations in brightness accompany

* See *Annals of the Solar Physics Observatory, Cambridge*, iv. 47, 1920.

† *Ibid.*, 52.

THE SPECTRUM OF NOVA GEMINORUM 1912

Photographed at the Cambridge Observatory, March 15-April 29, 1912



Nos. 1 and 12 are stationary enlargements showing the comparison spectra of iron. Nos. 2 to 11 have been widened by rocking.

On No. 2 are seen many broad bright bands and narrow absorption lines. In Nos. 3, 4, 5, and 6 the bright and dark hydrogen pairs have a wider structure and are doubled.

The stronger absorption lines in Nos. 2, 3, and 4 are mostly hydrogen lines or enhanced lines of iron and titanium characteristic of *a Cygni*. In Nos. 7 and 9 the strong absorption lines other than the hydrogen lines are nitrogen, oxygen and helium lines typical of γ *Orionis*. These are more displaced than the enhanced metallic lines, but with the same displacement factor as the more displaced component of the pair of dark hydrogen lines.

changes of spectra, the bright bands of Classes O and P being found for fainter stages than the bright bands of Class B. The nebular bands have a common structure very much resembling the structure of the hydrogen bands, whether these latter bands be examined at this stage or at an earlier stage. With some reservations it may be said that the intervals in the structure of the band vary directly as the wave-length of the corresponding line. Motion in the line of sight is still indicated as the best clue to the structure, though no simple scheme of jets, shells, or pulses fits all the facts.* It would be tempting to try and develop some explanation in terms of atomic structure, Stark effect or Zeeman effect, but one very important fact points markedly towards a Doppler effect. Shane and Moore † have shown that when the nova develops, as it appears to do generally, into a visible disc, some of the maxima in the bands come mainly from one part of the disc and some from another part of the disc. A complex system of rotations is indicated as a very important factor in producing the structure in the bright bands.

The final stage towards which nearly all novæ seem to tend is that of a Class O star of varying brightness. Recent evidence suggests that this Class O star is surrounded by an expanding nebulous disc, and it looks as though a nova reaches a not uncommon form of planetary nebula with a nucleus of spectral Class O. It has even been conjectured that the great majority of planetary nebulæ, and possibly some Class O stars also, sharing, as they do, the same galactic distribution, are the wrecks of novæ of past ages. It may be that from some of the complex forms of these nebulæ we may be able to work back to the movements found in the early stages of novæ, and that each type will, in turn, help to the understanding of the other.

* See Wright, *M.N.R.A.S.*, lxxxii. 191, 501, 1921.

† *Lick Obs. Bull.* No. 322, 1919.

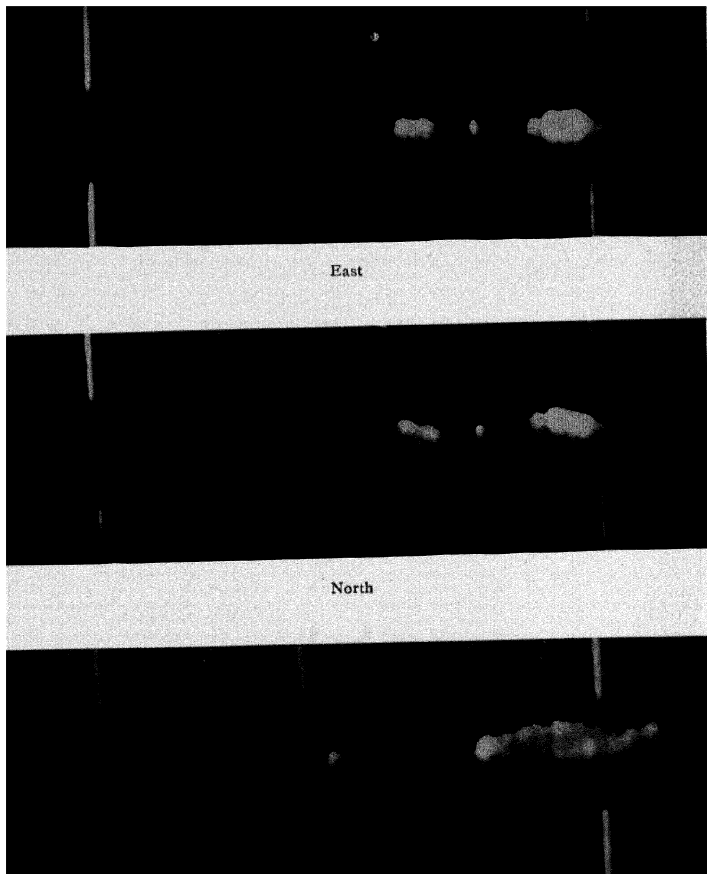
69. Novæ and Nebulæ.—N Aurigæ 1892, six months after its first outburst, was discovered to have brightened to a second lesser maximum, and to be showing broad, bright bands in its spectrum in the position of the principal nebular lines; since then, this development of a bright nebular spectrum within a few months of discovery has been found to be typical of novæ. The exact connection between a nova and a gaseous nebula is not yet clear. Ritchey, photographing the region round N Persei 1901 eight months after its appearance, found traces of nebulosity round the nova which later photographs showed to be moving rapidly outwards.* A study of the spectrum of this nebulosity by Perrine † showed that it resembled that of the nova at its stage of maximum brightness; this fact, coupled with considerations of the distance of the nova and the speed with which the nebulosity appeared to grow outwards, has led to the general view that what was photographed by Ritchey was the spread outwards of illumination from the central body, lighting up existing nebulosity. Similar results have not been found for any other nova as yet, but this connection of the outburst of N Persei 1901 with surrounding nebulosity should provide a most important clue in building up a theory of the origin of novæ.

The spreading bright nebulosity, which was observed in 1902, reaching to a distance of 20' from N Persei 1901, was, in all probability, not directly responsible for the nebular spectrum; it seems reasonable to attribute this spectrum to a much smaller nebular envelope which was discovered by Barnard in December, 1916, nearly sixteen years after the first discovery of the star; ‡ this nebulosity is nearly symmetrical round the stellar nucleus, and is apparently spreading outwards—having extended to a radius of over 8" by 1920. N Persei 1901, within twenty years of dis-

* *Ap. J.*, xiv. 293, 1901; xv. 129, 1902.

† *Ibid.*, xvii. 310, 1903.

‡ *M.N.R.A.S.*, lxxx. 721, 1920.



North

GREEN NEBULAR BANDS OF NOVA AQUILÆ, 1918, IN LATER STAGES

- (a) 1919, August 1, slit in position angle 112°
- (b) 1919, August 1, slit in position angle 112°
- (c) 1920, May 23, slit in position angle 202°

covery, had all the appearance of a typical planetary nebula—an unexpectedly rapid development when the usually accepted time-scale for stellar evolution is considered.

This smaller and later display of nebulosity spreading out from the central disturbance, has been paralleled by the spreading discs found for the two most recent bright novæ, N Aquilæ 1918, and N Cygni 1920. We have here almost certainly the outward spread of actual matter from the centre; we may note that the rates of growth of the discs taken in conjunction with the probable parallaxes of the novæ give velocities for the outward flowing gases which are consistent with high velocities of about 2000 km./sec. given both by the absorption lines in the early spectra and by the maxima in the subsequent bright bands. This is one of the important arguments in favour of an interpretation of the complex spectra of novæ in terms of a simple Doppler effect. Other disturbing conditions are undoubtedly present, but the outward flow of gaseous matter is one of the most important factors in producing the observed results.

70. The Later Stages of N Aquilæ 1918.—An extraordinarily interesting addition to our knowledge of the later spectra of novæ was made by Moore and Shane in the case of N Aquilæ 1918. Observing the nova with a slit set across the visible disc at a certain angle and the disc kept fixed on a given point of the slit, they discovered * that certain bright maxima in the spectrum are strong in one part of the disc and others strong in other portions of the disc (Plate 32). Roughly speaking, maxima displaced by equal amounts from the normal position of the corresponding spectral line are bright on opposite sides of the disc. If there were only two maxima, a simple interpretation in terms of two rotating arms would at once suggest itself. But the phenomenon is more complex than that. Rotations in opposite directions in the same plane are involved,

* *Lick Obs. Bull.*, No. 322, 1919; *Observatory*, xliii. 283, 1920.

and further difficulties arise from the fact that the growing disc is twice as large for the nebular lines as for the hydrogen. Two years after discovery, the diameter of N Aquilæ 1918 was $3''\cdot7$ for the green nebular lines, but only $1''\cdot5$ for $H\beta$. It is tempting to relate the outward growth of the disc with the maxima in the bright bands. But, while equal velocities are indicated for the nebular gases and for hydrogen by the displacements of the bright maxima, yet the two discs grow at different rates. As is to be expected in such catastrophes as occur when novæ are born, no simple explanation meets the facts. But as the disc of N Aquilæ 1918 grows, and the structure opens out and becomes visible, we ought to obtain some information of the greatest value from the study of slit and slitless spectrograms.

71. Theories as to the Origin of Novæ.—It has been suggested above that planetary nebulæ with Wolf-Rayet stars as nuclei represent the ultimate fate of novæ. What is to be said about their origin? What is the nature and cause of the catastrophe which results in the outburst of a new star? Three main lines of explanation have been offered. The simultaneous presence of the dark and bright line spectra naturally led to the suggestion of two stars colliding or passing so close to one another as to produce violent upheavals through tidal causes. The constant repetition of a dark line spectrum on the violet side of the accompanying bright band spectrum, the complicated structure of the bands—suggesting the need for more than two bodies—and the frequency of observed outbursts have all told against the explanation of novæ in terms of two colliding stars. The special form of this explanation adopted by Bickerton in which the two stars leave a glowing mass at the centre of disturbance, a mass shorn off the colliding bodies in their partial impact, has likewise failed to secure general acceptance.

The view that in a nova we see the outburst of im-

prisoned energy through a breakdown in the stability of the crust of a cooling star, fails to suggest a sufficient cause for the enormous forces at work, say, in N Aquilæ 1918, or for the growing disc of the later stages of the nova. It fails, also, to account for the distribution of the novæ in the sky : the region of the galaxy, the Magellanic clouds and a few spiral nebulæ include nearly all known novæ.

A clue that must not be overlooked is the nebulosity seen round N Persei 1901, illuminated by the light of the great initial outburst. A further clue may be found in the shapes of the planetary nebulæ which seem particularly likely to have developed from novæ. These are often helical and suggest a combination of rotation and translation in the source of the disturbance. Though no simple theory yet worked out in detail offers an explanation of novæ, the most hopeful line of attack would seem to be the study of the phenomena accompanying the collision of a star or a binary star system, with an extensive nebulosity. Seeliger * and Halm † have developed this theory, but so many new facts have been learnt since they wrote on the subject that their work requires to be greatly supplemented. The final theory of novæ has not yet been developed, but the most likely solution at present available seems to be in terms of the spreading out of streamers of glowing gases from a central body or bodies after a collision with a dark cloud.

72. Variable Nebulæ.—Confirmation of the explanation of novæ suggested above may be found in the variable nebula N.G.C. 2261, studied by Hubble ‡ and Brown.§ The latter has suggested that the fan-shaped appendage of this nebula with its rapid and irregular variations in light-giving power can be explained in terms of the passage of a

* *A.N.*, cxxx. 393, 1892; *Astronomy and Astrophysics*, xi. 904, 1892.

† *Proc. R.S. Edinburgh*, xxv. 513, 1904.

‡ *Ap. J.*, xlv. 190, 1916.

§ *Ibid.*, liii. 169, 1921.

star—the head of the fan—through a nebula consisting of a swarm of particles. In this connection it is suggestive that the spectrum of the nebula * is a bright-line spectrum, consisting mostly of hydrogen lines and lines due to ionized iron, familiar in the early stages of novæ ; further, the bright hydrogen lines are accompanied by dark companions on the violet side, as is the case with novæ. This variable nebula, and one or two others of like behaviour, are found in parts of the sky where there are dark spaces and accompanying diffuse nebulosity. † If this comparison and Brown's theory do have an application to novæ, it would seem that in these special cases the low relative velocity of the star and the cloud is mainly responsible for the absence of the great outburst of activity associated with novæ. The nucleus of each of these nebulæ varies in brightness. This is quite natural if the nucleus is a star passing through nebulosity of varying density and the brightness of the nebulosity would vary also ; there is, however, an alternative suggestion which must be mentioned, namely, that the variation of the nebula is directly connected with varying radiation from the stellar nucleus to which its own luminosity may be due (see § 61 above).

* Slipher, *Lowell Obs. Bull.*, No. 81, 1918. See also § 80 below.

† Knox Shaw, *Helwan Obs. Bull.*, No. 20, 196, 1920.

CHAPTER XII

VARIABLE STARS

73. Classification of Variable Stars. Eclipsing Variables.

—The classes in which variable stars may be grouped are many. For the present the International Astronomical Union has decided to maintain the five classes adopted by E. C. Pickering * : (1) Novæ ; (2) Long Period Variables ; (3) Irregular Variables, generally with small range in magnitude ; (4) Short Period ; (5) Algols, or Eclipsing Variables, which undergo for a short time with great regularity a marked diminution in brightness. We have already dealt with the novæ at some length. Long period and short period variables are treated in the following paragraphs.

Eclipsing variables are naturally closely connected with spectroscopic binaries (see Chapter VII above). Here we need only mention that the shape of the light curve when compared with the radial-velocity curve, gives a good indication as to the nature of the system. We are able to determine from the light curve alone the relative sizes and brightness of the two stars, the eccentricity of their orbit round one another, the nature of the eclipses (whether partial or total) and even, with certain reasonable assumptions, the amount of darkening at the limbs of the two components and the elliptical shape of the stellar discs. With a knowledge of the velocity-curve we can get the

* *Proc. of the American Academy of Arts and Sciences*, xvi. 17, 1880.

actual dimensions of the orbit and of the component stars.* The general results found have been that for a range of variation of over one magnitude[‡], the fainter star is larger and redder than its companion. For smaller ranges of variation, the two stars are more frequently nearly equal in magnitude. The gravitational elongation of the stars along the line joining them comes out in very fair agreement with Darwin's theoretical value for a homogeneous, incompressible fluid.† Further suggestions made by Dugan ‡ to improve the fit of the observed light-curve to the calculated curve are that the sides of the stars turned towards one another are brighter than those turned away from each other, and also that the advancing side of the brighter or eclipsing star is brighter than the following side. What is probably an unusual type of eclipsing variable, β Lyræ, is dealt with in the next chapter (§ 82).

74. Irregular Variables.—It is naturally not easy to classify the irregular variables. There are, however, two or three groups which deserve special mention. There are twelve stars which resemble R *Coronæ Borealis* in that they remain of constant magnitude for long intervals of time, but are subject to occasional sudden drops in brightness of uncertain amount (sometimes through several magnitudes) and of uncertain date and duration. The spectra of this group of stars generally include bright lines, in several cases resembling novæ at an early stage. In R *Coronæ Borealis* the hydrogen lines are absent from a spectrum of Class F5, this being possibly a transition stage between bright and dark

* See Russell and Shapley, "On Darkening at the Limb in Eclipsing Variables," *Ap. J.*, xxxvi. 239, 385, 1912; and Shapley, "The Orbits of Eighty-Seven Eclipsing Binaries—a Summary," *Ap. J.*, xxxvii. 158, 1913.

† *Phil. Trans.*, ccvi. A, 161, 1906.

‡ *Contributions of the Princeton Univ. Obs.*, No. 2, 42, 1912; No. 4, 22, 1916.

hydrogen lines. Ludendorff has suggested * that the loss of brightness may be due to the passage of the star behind patches of nebulosity and the bright lines in the spectra may be connected with passage through a nebular cloud. One of the stars in the group *T Tauri* has been found to lie in faint nebulosity to which the bright lines in its spectrum are probably due.† The whole group lie in low galactic latitudes.

Another group of seven irregular variables, with *U Geminorum* as typical star, is to be found in a wide range of galactic latitudes.‡ These stars keep at constant or nearly constant brightness save for occasional rapid increases in brightness—through an average of four magnitudes and in a few days. The return to the normal brightness is slower, the light curve resembling that of a nova, except for the smaller range of magnitude concerned. The spectrum of two of them is known. In each case it is a variable spectrum of Class F with occasional bright lines present and a suggestion of two spectra blended together. In view of the position of these stars in space, something in the nature of a prominence outburst on a large scale rather than collision with nebulosity would seem to be indicated as the cause of the brightening.

There is a small group of variable stars, called by Ludendorff the *RV Tauri* class,§ which have secondary oscillations in their brightness, though these secondary oscillations are not in constant phase-relation with the principal oscillations as in the case of eclipsing variables. These stars appear rather to link on through a small group of stars, of which *R Centauri* is typical, to the ordinary long period variables of Class M. In *R Centauri* the maximum is divided into two by a secondary minimum.

75. Long Period Variables.—The great majority of the

* *A.N.*, ccix. 273, 1919.

† Pease, *Ap. J.*, xlv. 89, 1917.

‡ *A.N.*, ccxiv. 221, 1921.

§ *A.N.*, ccxiv. 217, 1921.

long period variables have a range in brightness of about five or six magnitudes, and a period of about a year. They rise to light-maximum more rapidly than they fall to light-minimum. They have a continuous spectrum containing numerous absorption lines and bands due to chemical compounds, those of titanium oxide (Class M) being much more commonly found than those of zirconium oxide (Class S) or carbon bands (Classes R, N). Bright lines are superposed on this absorption spectrum, the lines varying in brightness with different phases of the light-curve. The typical star of Class M is α *Ceti* or *Mira*. Amongst the bright lines are the Balmer lines of hydrogen (H δ being frequently far the most conspicuous line), and low temperature arc lines of iron, magnesium and silicon ; * there are curious indications of a few lines due to ionized metals.† The particular selection of bright lines found has yet to be explained by laboratory experiment, as also the peculiar variations in intensity of the hydrogen lines.‡ The absorption bands increase in intensity, as the star fades, while the bright lines of the different elements and even lines of the same element reach their maximum intensity at different stages of the light-curve.§ The hydrogen lines are the first bright lines to appear, shortly after light-minimum ; they reach maximum brightness shortly after light-maximum for M stars (and shortly before light-maximum for N stars) ; the bright iron and magnesium lines appear later in the light-period, and reach their maximum intensity at different phases, the

* Stebbins, *Lick Obs. Bull.*, No. 41, 1903 ; Adams and Joy, *Pub. A.S.P.*, xxx. 193, 1918.

† Cf. the 9th companion to Castor also α^* *Eridani*-C, both of which have bright [H] and [K] on an Me spectrum. *Pub. A.S.P.*, xxxii. 158, 1920, and xxviii. 323, 1921.

‡ In the case of α *Ceti*, some of the anomalies are to be explained by the presence of a faint companion of spectrum B8ep with bright lines, due to hydrogen and ionized metals.

§ Merrill, *Ap. J.*, liii. 185, 1921.

magnesium line at λ 4572 reaching maximum brightness not long before light-minimum. The marked faintness of several of the bright hydrogen lines is best accounted for by their being lost in strong absorption lines, e.g. H ϵ is very faint on account of its lying within the strong calcium absorption line [H]. This, however, does not explain all the anomalies in the relative brightness of the lines of the Balmer series.

We have already seen that in the case of the long-period variable R *Aquarii*, certain of the well-known nebular lines have been found bright,* such as 5007, 4959, 4658, 4363, 3869, and also the helium line, 4471. These lines remain constant in brightness throughout the period, and are apparently accompanied by constant bright hydrogen lines, on which are superposed bright hydrogen lines varying with the brightness of the star. The hydrogen lines of constant intensity follow the nebulae in their relative brightness, H β being stronger than H δ . It seems reasonable, in view of the discovery of surrounding nebulosity to ascribe these constant lines to a nebular envelope which has been photographed and found not to share in the fluctuations in brightness of the stellar nucleus. R *Aquarii* also shows bright at minimum the low-temperature magnesium line λ 4572, in this, as in other respects, resembling the long-period variables of Class M.

An interesting application has been made of the vacuum thermo-couple in studying the total radiation from *o Ceti* at different stages of the light curve.† The total radiation changed in amount considerably less than the visual radiation, probably because the visual region of the spectrum lies on the violet side of the wave-length of maximum energy of the radiation. A small shift of the maximum would mean a large drop in the apparent brightness, which

* Merrill, *Ap. J.*, liii. 375, 1921.

† Nicholson and Pettit, *Pub. A.S.P.*, xxxiv. 132, 1922.

affords an explanation of the large range in magnitude in the low-temperature variables. The use of a water-cell in front of the thermo-couple helps in the determination of the distribution of the spectral energy and of the corresponding stellar temperatures. Milne * has given a preliminary estimate of the range of temperature of α *Ceti* as 3000° at maximum, to 1700° at minimum.

It has been pointed out by several writers † and confirmed by Ludendorff ‡ from the latest material available that the period, the amplitude of variation and the spectral type of the long-period variables are closely related. The range of variation increases with the period, and at the same time the star's spectrum is of later type.§ It is not easy to say whether the presence of bright lines in the spectra, which distinguishes the stars of Class Me (or Md) from Classes Mo, M₃, M₈ (or Ma, Mb, Mc), affects the period. It is true that, on the whole, the Me stars are of longer period, but this is largely accounted for by the fact that later type stars are more frequent among the Me stars than among the M stars which show no bright lines. Nearly all the M variables with periods of over 400 days are Me stars.

The Me stars are probably all giants,|| and it would not be surprising if their periods differed from those of dwarf M stars, but the usual separation into two classes has not yet been made by the criterion of period.

Another factor which varies with the period is the displacement of the bright lines relative to the dark lines. The bright lines are displaced towards the violet relative to the dark lines by amounts indicating relative velocities of

* *Observatory*, xlv. 223, 1922.

† See Gyllenberg, *Arkiv för Math., Ast. och Fys. K. Svensk. Vetenskap.*, xiv. No. 5, 1918.

‡ *A.N.*, cccix. 1, 1923; ccx, 145, 1924.

§ Merrill, *Ap. J.*, lvi. 472, 1922. Perrine, *Pop. Ast.* xxxii. 562, 1924.

|| *A.J.*, xxxiv. 190, 1923.

7 km./sec. for stars of 200 days period, and 18 km./sec. for stars of 375 days period. Merrill found * that the displacements were not constant throughout the cycle, but were most marked for a month or two after maximum light. It should be remembered that in the case of *o Ceti*, where the spectrum has been photographed throughout the cycle the anomalous behaviour of the bright and dark lines was partly explained by the discovery of a faint companion of early spectral type. This observation was made by Aitken at the suggestion of Joy,† who hoped in this way to clear up some puzzling spectroscopic observations.

There is slight but definite evidence that the brightness at maximum is greater for the longer-period variables ‡ and that the stars of longest period affect the plane of the Milky Way.§ Another characteristic that changes with the period is the light-curve.

The steepness of the rise from minimum to maximum is most marked with the longest periods. The light-curves of the long-period variables cannot be represented accurately by a simple sine-curve, but over long intervals of time a good representation can be given by the use of two or three harmonic terms.|| Phillips ¶ has divided the variables into two groups according as certain relations exist between the phases of the harmonic terms. If the magnitude is represented by the expression :

$$M + P \cos(\theta - 180^\circ) + P' \cos(2\theta - \phi_2) + P'' \cos(3\theta - \phi_3),$$

then the variables group themselves into (a) Group I, for which ϕ_3 is always nearly 200° , while ϕ_2 may have any value within a wide range; and (b) Group II,

* Merrill, *Ap. J.*, lviii. 236, 248, 1923.

† *Pop. Ast.*, xxxi. 237, 645, 1923; *Pub. A.S.P.*, xxxv. 323, 1923.

‡ Ludendorff, *A.N.*, ccxx. 150, 1924.

§ Turner, *M.N.R.A.S.*, lxxix. 373, 1919.

|| See Turner, *Mem. R.A.S.*, lv. 97, 1904.

¶ *Journal B.A.A.*, xxvii. 5, 1916.

for which there is a linear relation between ϕ_2 and ϕ_3 , namely, $\phi_3 = 1.67\phi_2 - 126.8^\circ$. Hagen * pointed out that Phillips's Group I corresponded to stars whose variation was nearly uniform, the time from minimum to maximum being only just less than half a period, and there being no long pause at the maximum or at the minimum. Phillips's Group II Hagen sub-divided into those with a rapid increase of magnitude, whose light-curve resembles the sun spot curve, and those with broad minima. There seem to be certain physical differences corresponding to Phillips's groups, the stars of shorter period (< 200 days) and shorter range of variation belonging to Group I.

For Class N stars, Ludendorff † finds that the range of variation in magnitude is less than for the stars of Class M, of which *o Ceti* is the type. This would seem to indicate higher temperatures for Class N stars. In respect, also, of steepness of rise to maximum, Class N stars differ from *o Ceti* in the same sense as stars of Classes K, Mo, M3. But, in one respect, they differ in the other direction: the average period is greater than for the ordinary long-period variables, being nearly 400 days instead of about 300 days. The Class N stars, like the Class Me stars, are all giants.

Data of the above nature provide the material by which the views of the theorist as to the early stages of stellar evolution must be checked. The present position seems to be that stars, when they first become visible as condensing masses of cool gas, appear as Me (or N stars), varying in brightness in a period between one and two years. At this stage of their history the sequence of stellar spectra, M8e to Mo, probably represents the line of evolution; the star's temperature rises, its oscillations in brightness become less extreme and shorten in period, the brightness of the star at maximum slowly diminishes, and the star approaches a

* *Ap. J.*, liii. 179, 1921.

† *A.N.*, ccxvii. 161, 1922.

stage of radiative equilibrium. Gradually, changes in the spectra due to growing condensation and rising temperature are followed by the much slower changes due to diminishing mass, but by the time that mass has become the determining factor, the star has probably ceased to figure in the catalogues of variable stars.

76. Short Period Variables.—A few stars with periods ranging from 90 days down to 35 days have been grouped by Ludendorff as possibly representing a transition stage from the long-period variables to the Cepheids (called after the type star δ *Cephei*). There is a gap between 45 days, and 67 days with only one star to fill it which comes approximately at the change from Class M to Class K. Whether this gap indicates that there is no proper transition from one class of variable to the other, or that the transition stage is passed through comparatively quickly, cannot yet be decided. A similar gap occurs among the short period stars for periods between 3 days and 1 day; this gap divides them into two groups, to which the names cluster variable (for the periods less than 1 day),* and Cepheid variable (for periods from 3 to 40 days) have been allotted by certain writers. This second gap does not correspond to any other established physical difference between the Cepheid and cluster variables, although it does correspond to a difference in distribution. The Cepheids or variables with periods from 3 days to 40 days are confined to low galactic latitudes,† while the variables with periods of less than one day are found in all galactic latitudes. In the questions of distribution and the connection of the period with the shape of the light-curve there remain unsolved problems as with the long-period variables, but, on the whole,

* The shortest known periods are 3 h. 14 m. 5.8 s. for a cluster variable in Messier 3 discovered by Larink (*A.N.*, ccxiv. 71, 1921), and 5 h. 41.6 m. for a faint eclipsing variable of β *Lyræ* type found by Jordan at 12 h. 28 m. 4 s., and + 27° 16.1' (*A.J.*, xxxv. 44, 1923).

† And to spiral nebulae; *Pop. Ast.*, xxxiii. 252, 1925.

it seems reasonable to link the Cepheid variables on to the long-period variables. This can be more readily accepted, since the old explanation of a Cepheid as a special case of a binary star has proved very difficult to fit in with the following observed facts. On the assumption that a Cepheid is a binary, it is possible to determine the elements of its orbit and the probable sizes of the component stars. Only too frequently the radius of the orbit comes out at a smaller figure than the sum of the radii of the component stars. Again, the spectrum of a Cepheid variable changes continuously in two respects during its light period; the displacements of the lines change continuously, the highest velocities of approach coinciding with maximum brightness, which is not in accordance with the normal condition for a variable binary; also light-maximum corresponds to a star generally a whole Harvard class earlier in type than the star at light-minimum; at no time is there evidence of a secondary spectrum alongside the primary; changes in the colour-index and in the relative strength of various lines indicate higher temperature and greater ionization at maximum; the mean absolute magnitude of the star and also the mean colour-index are simply related to the period of the variation. Everything points to an explanation in terms of one body instead of two. A theory has been worked out by Shapley* and Eddington,† according to which the behaviour of a Cepheid variable is interpreted in terms of a single pulsating star. There are some outstanding difficulties in the narrowness of the absorption lines and in the long-continued maintenance of the pulsation, but the theory at present holds the field. It has even been used by Eddington‡ to deduce, from the observed slight decrease, about 0.1 sec. per annum, in the period (5.366 d.)

* *Ap. J.*, xl. 448, 1914.

† *Observatory*, xl. 290, 1917; *M.N.R.A.S.*, lxxix. 2, 177, 1918.

‡ *British Association Report*, 1920, 45.

of δ *Cephei*, a criterion as to the true time-scale for stellar evolution. We are not here, however, in the region of assured knowledge, as witness the fact that for η *Aquila* the present evidence points to an increasing period,* which is inconsistent with the pulsation theory. It is possible that some short-period variables may be wrongly classed with the Cepheids and may be eclipsing variables, in whose case the simple phenomena of an eclipse are modified by tidal disturbances. The main bulk of the short-period variables, however, must be classed as single stars.

Certain laws governing them have been discovered, and have provided an important clue to the scale of the stellar universe. Thus Miss Leavitt discovered † that for the Cepheid variables in the Magellanic clouds there was a connection between luminosity and period—the brighter variables having the longer periods. Shapley has extended these results ‡ showing that the relation between the mean absolute magnitude and the period of a short-period variable is very close, the absolute magnitude, and, therefore, the distance of a Cepheid variable being determined from its period with only a small probable error. The chief application has been made to the variables with periods less than one day which occur commonly in globular clusters and give parallaxes for these clusters. The greatest distance found for any cluster by this method was for N.G.C. 7006, a distance of 220,000 light-years or 70,000 parsecs. As we have seen already (§ 64) Hubble used the same method to determine the distance of the Andromeda nebula, finding consistent results from 12 Cepheid variables and a value of 950,000 light-years.

The luminosity of a Cepheid variable is always very high; the absolute photographic magnitude comes out always brighter than -0.2 , § the redder variables being brighter

* Wylie, *Ap. J.*, lvi. 231, 1922; Hellerich, *A.N.*, ccxxii. 25, 1924.

† *Harvard Annals*, lx. 107, 1908; *H.C.O. Circular*, 173, 1912.

‡ *Ap. J.*, xlviii. 104, 1918.

§ *Ibid.*, xlix. 96, 1918.

than the bluer ones. The physical implications underlying this limiting magnitude remain to be worked out as part of the general problem of stellar variation.

Shapley's conclusions are based on the assumption that the luminosity curve for a cluster variable is the same as that for other short-period variables. Henroteau,* on the other hand, has suggested that cluster variables are of smaller mass than the short-period variables in the galaxy; also that in accordance with the general dependence of temperature and spectrum on mass, the cluster variables are less luminous than the others and less distant than Shapley finds them to be. If Henroteau's separation of the short-period variables into groups of different mass is to be accepted, it may indicate that a dependence of stability on stellar mass is the deciding factor in causing the gaps in the observed periods of variables, to which reference has been made above.

One very important application has been made of the study of cluster variables. Examining the light curves in blue and yellow light for a number of variables in the cluster Messier 5, Shapley † found that the delay in the photographic median magnitude on the photovisual median magnitude came out at 0.00012 d. ± 0.0007 d. or well within the probable error of the determination. This meant that blue light travelled for 40,000 years without lagging more than a minute or two behind the accompanying yellow light or that the velocities agreed to one part in twenty thousand million. The lack of evidence for dispersion of light in so long a journey has a bearing on the question of the presence of absorbing matter in space and on the size of the particles of which such matter must be composed. The implication is that if any such matter lie between us and Messier 5, it is

* *Pub. Dominion Obs., Ottawa*, viii. 80, 1923.

† *Proc. N.A.S.*, ix. 386, 1923.

composed of particles whose linear dimensions are not of the order of a wave-length of light.

77. Theories of Stellar Variation.—We have seen how diverse are the different types of variables. It is natural that many explanations should have been brought forward to account for them. The simple eclipsing of a bright star by a faint companion accounts naturally and successfully for the Algol variables, but fails to account for the short-period or Cepheid variables. For this, pulsation accompanied by changes in temperature, luminosity, colour-index and spectrum is suggested as the principal factor in the observed changes. For the long-period variable the veil theory, which attributes the variation to periodic changes in the transparency of the outer atmosphere of the star only, seems the most suitable. The condensation of clouds of small particles at regular intervals * can be reconciled with the occasional discontinuities detected by Turner † which would be due to the action of some disturbing force either inside or outside the star. One class of irregular variable may brighten sporadically through the breakdown of an outer crust and an outrush of hot gases from the interior, while other classes of irregular variables may be explained as caused by the passage of stars through or behind nebulosity : an occasional irregular brightening may be due to collision of star and nebula, an occasional fading to occultation of the star by nebulosity. When the relative motion of star and nebulosity is sufficiently great, a collision may result in the outburst which we associate with a nova.

* P. W. Merrill, *Pub. of the Observatory of the University of Michigan*, i^o 70, 1916.

† *M.N.R.A.S.*, lxxvi. 480, 1916.

CHAPTER XIII

STARS WITH PECULIAR SPECTRA

78. Fixed Calcium Lines.—In this chapter it is proposed to deal with some of the principal types of stellar spectra which stand outside the normal sequence. In most cases no solution has been proposed for the problem offered by the abnormality in the spectrum, but we start with a case where several solutions have been proposed. A certain number of early Class B stars, whose lines show variable velocity, have present in their absorption spectrum two fixed lines [H] and [K] due to enhanced calcium. Occasionally, as in the case of δ *Orionis*, the sodium [D] lines are also present fixed in position.* The velocities shown by these fixed lines are always small when the motion of the solar system has been taken into account. In the special case of novæ, where these lines are also seen, the velocity given by these lines is the solar component reversed, within the error of measurement. The same holds good of J. S. Plaskett's very massive binary, B.D. 6° 1309, the most massive star but one so far known.† In the case of other binaries the velocity given by the stationary [H] and [K] lines is frequently coincident with the small velocity of the centre of inertia of the binary system; less frequently it shows a different velocity and occasionally it shows a velocity varying with the period

* *Lick Obs. Bull.*, No. 326, 1919; No. 337, 1921.

† *M.N.R.A.S.*, lxxxii. 456, 1922. The probable masses of the components are 86 and 72 times the mass of the sun. ν *Sagittarii* is at least twice as massive (see § 39).

of the binary, but with less range than that given by the other lines. J. S. Plaskett has recently shown * that in the case of Class O stars the [H] and [K] lines, also the [D] lines, give velocities distinct from those of the corresponding stars, and within the error of measurement agreeing with the reversed solar velocity.

Two main theories have been proposed for these lines. The one postulates dark interstellar clouds, mostly fixed in space and containing a sufficient proportion of atoms of ionized calcium and of sodium in the right condition to show the absorption lines on the continuous spectrum of the stars. The difficulty about this explanation lies in the fact that the types of star in which these lines occur are strictly limited; this is not wholly to be explained by the further fact that these types are the ones best able, from the nature of their spectra, to show the narrow fixed calcium lines. The alternative explanation which found favour with R. K. Young, † is that these lines bear witness to the presence of an outer envelope to the binary star system, which does not share in the oscillations of the binary contained within. There is a difficulty here in that the radial velocity given by the [H] and [K] lines is not always the same as that of the centre of inertia of the binary. The further difficulty of explaining the presence of this outer envelope has to be faced. It is not impossible that in these stars, representing largely the most massive stars, radiation has become so important, relatively to gravitation, that an outer envelope of light gases has been driven out from the central body. Evidence for such outflow of gases followed by the presence of stationary calcium lines is to be found in the history of novæ.

A third solution proposed by H. H. Plaskett, ‡ is an ingenious combination of the two previous theories. According

* *M.N.R.A.S.*, lxxxiv. 80, 1923; *Pub. D.A.O.*, ii. 341, 1924.

† *Pub. D.A.O.*, i. 225, 1920. ‡ *Ibid.*, ii. 342, 1924.

to this view, the intervening cloud postulated in the first hypothesis is near enough to the high temperature star to have enough calcium atoms ionized by the radiation from the star to enable the cloud to show the sharp [H] and [K] lines superposed on the stellar spectra. Some of the Class O stars which show sharp [H] and [K] lines are involved in luminous nebulae. The extension suggested by Plaskett is that others are involved in or are close behind widespread calcium clouds which are, for the most part, much less dense than the dark clouds recognized by their obscuration of the stellar background. The anomalous cases where the [H] and [K] lines seem to share partly in the oscillations of the lines of Class B binaries may be accounted for by a blend of lines due partly to a stationary cloud of calcium and partly to a moving stellar calcium atmosphere.

79. Former Novæ.—Two of the novæ of history are now surviving as fairly bright variable stars with peculiar spectra. They do not seem to have followed what we may call the usual course, ending as faint Class O stars surrounded by nebulosity, but they seem to have found unusually stable conditions at some earlier stage of their evolution. *P Cygni*, previously unrecorded, was discovered by Janson on 18th August, 1600. It was observed by Kepler two years later as of the third magnitude, and it ceased to be visible to the naked eye in 1621. It became of the third magnitude again in 1655, but by 1677 it had dropped to magnitude 5.0, and it has maintained nearly constant brightness since. In the slowness of its fading and in the relatively bright condition of stability it differs so markedly from the typical nova that one would be inclined to place it with the irregular variables rather than with the novæ if it were not for its present spectrum, which at once recalls a nova by its type. There are bright lines of hydrogen, helium, oxygen, and nitrogen with dark companions on the violet side.* In the width

* *Ap. J.*, xxxv. 286, 1912.

of the bright bands, and in the displacement of the companions the evidence all points to less violent forces at work than with the other novæ. It is tempting to suggest that the more moderate conditions obtaining are connected with the stability in this case of what is generally a very transitory stage with novæ. In terms of the collision theory of novæ, the suggestion would be an unusually small relative velocity of star and nebula.

Another nova which maintains an unusual and interesting spectrum is T *Coronæ Borealis* (a star of the second magnitude in 1866), the first nova to have its spectrum investigated. Huggins* noted the bright hydrogen lines superposed on a continuous spectrum with many absorption lines. Over fifty years later this star's spectrum was observed † and found to be of Class Mo, with bright hydrogen, helium, and nebular lines; the spectrum naturally recalls that of R *Aquarii*.

80. Nova Types.—It may here be mentioned that every recognized stage of the quickly varying spectrum of a nova seems to be paralleled in some star, apparently in a much more stable or steady condition. We have given some instances already. R *Monocerotis*, the nucleus of Hubble's variable nebula (see § 72 above), has, like the nebula, a bright line spectrum of hydrogen and ionized metals with dark lines on the more refrangible side of the hydrogen lines. One other variable, notably R *Coronæ Australis*, which is also linked to a variable nebula, shows the same type of spectrum.

Perrine ‡ has pointed out that the well-known Wolf-Rayet star, γ *Velorum*, shows still another resemblance to novæ. He has found that absorptions seen at the violet end of broad strong helium bands are sometimes double

* *Proc. R.S.*, xv. 146, 1866.

† *Pub. A.S.P.*, xxxiii. 263, 271, 1921.

‡ *Ap. J.*, lii. 39, 1920.

and vary rapidly in displacement as in the early stages of novæ; in eight days he gets an increase in radial velocity indicated by the helium absorptions from -597 km./sec. to -1169 km./sec. The phenomena require further study for their elucidation, but outgoing streams or shells of gas seem indicated.

Another star which bears some close relation with *P Cygni* and with novæ generally is DM + 11° 4673, a star of magnitude 7.7 studied at Michigan by Merrill.* Here, again, we have bright hydrogen lines with dark companions on the violet side and bright lines due to ionized metals, mainly iron, with dark lines due to helium and ionized silicon. The simultaneous presence of an absorption early B Class spectrum and of an emission A Class spectrum is paralleled in N Geminorum 1912. In the case of DM + 11° 4673 we have no evidence of past history as a nova. What we have is a stage, which is of short duration in a nova, existing under apparently stable conditions.

J. S. Plaskett has recently reported another remarkable star with a variable spectrum,† DM + 5° 1267. At times the spectrum is closely like that of *P Cygni*, bright hydrogen lines with dark companions displaced to the violet and in addition a displaced absorption spectrum of diffuse and rather weak helium lines. Some of the hydrogen absorption lines are doubled by bright centres. In addition, dark [H] and [K] are present and strong, and Mg II 4481 is present but weak. Then the metallic lines strengthen relatively to the helium lines, while at the same time the displacement of the hydrogen absorption lines to the violet is markedly increased. Next emission begins to appear for the lines due to ionized iron, titanium and chromium which form the familiar spectrum of *a Cygni* and of the early stages of novæ. These metallic emission lines are later accompanied on the violet

* *Pub. of Observatory of Michigan*, ii. 71, 1916.

† *Pub. A.S.P.*, xxxv. 145, 1923.

side by absorption lines which strengthen rapidly, the bright metallic lines weakening until the spectrum becomes very like that of *a Cygni*, with the addition of the complex bright hydrogen lines with their displaced dark companions. The displacements of all the absorption lines except the hydrogen lines are small. Taking into account the curious resemblances between the changes in the spectrum of this star and those occurring in the early stages of a nova, we may hope from a study of this star to get further insight into the puzzling problem of the novæ.

81. γ Cassiopeiæ.—Secchi, in 1866, found bright lines in the spectrum of γ Cassiopeiæ. This star shows the bright lines of hydrogen and ionized metals, principally iron, along with dark lines of nitrogen, oxygen, and helium. It does not resemble novæ in having dark companions on the violet side of the bright lines, but it is reminiscent of a later stage of a nova's spectrum. Thus, the bright bands are some 5 tenth-metres broad, the breadth being proportional to the wave-length, and bearing the same proportion for different elements. Again, Curtiss * has shown that the bright bands are bordered by several narrow components on each side symmetrically placed on both sides of the centre of the bands and more than doubling their widths. Again, approximately equal intervals separate successive outer maxima of a band. The analogy of a nova would suggest that we look to some extensive atmosphere of the star, coupled with some regularity of circulation in this stellar atmosphere to account for the structure of the maxima in the bands. If such an explanation were acceptable, we might escape the need of explaining the absorptions which reverse centrally and flank strongly the central bright maximum; but the presence of a strong continuous spectrum in this star makes it evident that these absorption bands are real and have to be accounted for in any theory proposed. The existence of

* *Pub. of Observatory of Michigan*, ii. 21, 1916.

an extensive outer atmosphere seems a likely and suitable hypothesis to adopt. It is supported by the temperature 6800° K (very low for a Bo star), indicated by the continuous spectrum. Milne has explained this as due to the molecular scattering of the radiation of shorter wave-lengths by an extensive outer atmosphere. Spectroscopic or photographic evidence must be sought for to confirm the actual existence of this envelope.

The star μ Centauri* closely resembles γ Cassiopeiæ in the simultaneous presence of a dark line B type spectrum and a bright line spectrum of hydrogen and ionized metals, ionized iron being the most prominent element represented. The star η Carinæ (or η Argus) also shows these bright metallic lines, accompanied by many bright lines of unknown origin. This star has many unknown lines in common with Hubble's variable nebula (see § 72 above), but the elements concerned and the physical condition involved have not yet been discovered.

82. β Lyræ.—A more complex problem has to be unravelled in the case of the variable β Lyræ. In this star we have the following factors present. First and simplest there is an absorption spectrum of type B8 which is displaced periodically in the same period as that of the complete magnitude variation 12.9 days. This spectrum changes in displacement normally as though it were the spectrum of one component of a spectroscopic binary of small eccentricity with a range in radial velocity of 369 km./sec. The curve of the light period has two minima as in the case of a normal eclipsing binary, and this B8 spectrum drops slightly in intensity at the principal minimum, suggesting that the component to which it belongs is the brighter of the two stars of the binary system. Rossiter† has detected in the velocity-curve a secondary oscillation, visible near principle minimum, due to the rotation of the partially

* *Proc. R.S.*, lxxiv., 548, 1905.

† *Ap. J.*, lx, 15, 1924.

eclipsed component. The other absorption spectrum, which diminishes rather more markedly in intensity at the secondary minimum of brightness, is of Class B5. The star to which it is presumably to be ascribed, shows only very small, if any, fluctuations in radial velocity, and is presumably far the more massive component of the two. In addition to these absorption spectra—and undisplaced [H] and [K] lines of calcium, as so often found in early B type binaries*—there is present a spectrum of bright bands of varying intensity and structure which agrees in selection of lines fairly well with the B5 component. Where the bright bands occur we often find other dark lines present which may be structural in the bright bands, or at least refer to the same source as the bright bands and, perhaps, the B5 absorption lines. In some cases we may have, corresponding to one spectral line, a B8 component with its appropriate displacement, a B5 component with its appropriate displacement, a broad, bright band (several Angström units broad), and several narrow absorption lines crossing or bordering the bright band. In some cases these extra absorption lines show a regularity of structure which seems to relate them closely to the bright band. Similar phenomena have been noted for novæ and for such a star as γ *Cassiopeiæ*.† In the case of β *Lyræ* this regularity of structure is almost more pronounced. Curtiss gives as the displacements of the dark components of H γ from the normal positions of the line — 7.30, — 5.89, — 4.56, — 3.17, + 2.20, + 3.32, + 4.48, + 6.73 Å. Save for the sixth and eighth components the spacing is very regular, the missing centre components being possibly blended with the B5 or B8 absorption.

Many theories have been proposed to account for the complex phenomena of β *Lyræ*. Most of them postulate a binary system in an early stage of evolution with the two

* See § 78 above.

† See § 81 above.

components close together and involved in an extensive atmosphere. According to this view the bright bands are due to the gaseous envelope in part, but also in part to one of the two stars, the variations in the intensity curve of the bright bands being due partly to eclipses of this star and partly to the varying absorptions which its light undergoes in different phases. The width of the bands is due mainly to the rotation of the gaseous envelope, as in the case of novæ. The regular structure in the bands may be traced to the same cause as in novæ (i.e. some regularities in the rotational movements of the envelope) or else to some system of regular and successive reversals of lines due to abrupt changes in the density gradient; it cannot, however, yet be claimed that we have found the key to the problem.

83. Elements Abnormally Strong.—A few stars may be mentioned where the lines of a single element come out more strongly than in general with stars of closely allied spectral condition. Thus we have α *Canum Venaticorum*, a star of spectral class Aop, in which europium is present in a group of lines varying periodically in intensity* and displacement in a manner which suggested to Belopolsky a rotating outer layer or ring of gas. Again, in α *Andromedæ*, Class Aop, we have the lines of ionized manganese present in unusual strength.† In ϵ *Ursæ Majoris*,‡ Class Aop, we have ionized chromium similarly very strong, while in α *Cygni*§ and γ *Cygni*|| we have ionized iron and titanium respectively strongly present. ϕ *Cassiopeiæ*, Class F5,¶ is

* *Bull. de l'Academie Imperiale de Sciences de St. Petersburg*, VI Series, vii. 689, 1913; Baxandall, *M.N.R.A.S.*, lxxiv. 32, 1913.

† *M.N.R.A.S.*, lxxiv. 250, 1914.

‡ "Researches of the Chemical Origin of Various Lines in Solar and Stellar Spectra, Solar Physics Observatory," 1910.

§ Catalogue of 470 of the Brighter Stars, Solar Physics Observatory, 1902.

|| J. N. Lockyer and Baxandall, *Phil. Trans.*, cci. A, 205, 1902.

¶ W. J. S. Lockyer and D. L. Edwards, *M.N.R.A.S.*, lxxxi. 479, 1921.

transitional between these two so far as iron and titanium and other elements are concerned, but shows ionized strontium slightly stronger than both the others do. Possibly considerations based on Saha's theory will, in time, enable an investigator to place these and other similar stars in an ordered sequence on the giant side of the evolution ladder, but at present they seem to be just outside the main spectral sequence.

CHAPTER XIV

SPECULATIONS IN COSMOGONY

84. Stellar Evolution.—The stellar spectra form a simple linear sequence, and it has generally been thought that the course of evolution for individual stars is either along this sequence in the same direction for all stars, from high to low temperatures, or else along the sequence from low to high temperatures, returning along the same sequence to low temperatures. In both theories the star has been presumed to be condensing steadily from an initial tenuous mass of very low density. Eddington has cut right across these views by showing that if a star is in radiative equilibrium its luminosity and its mass are closely related to one another, and that the sequence of spectra represents a sequence of equilibrium points for the evolution of stars of different mass but by no means necessarily a sequence of stages through which individual stars will pass. The probable course of evolution of a star is along the line of decreasing mass and decreasing luminosity. On the whole we should expect that, if the sequence does represent the course of evolution, we should find that luminosity diminished as we pass along the sequence in the direction in which change is taking place. There is some evidence that at both ends of the spectral sequence O-B-A and M-K-G the luminosity diminishes, as we pass along the sequence from the extreme type, and this suggests that both the O and the M stars may represent early stages in stellar evolution. So far as the Class O stars are concerned, their masses average

fifty times the mass of the sun, while the average mass of a Class B star is only ten times the mass of the sun.* This also indicates, on the whole, an evolution from O to B rather than from B to O.

We may look to see what the two classes of stars O and M have in common, beside their great mass and luminosity, which may support this view. They both have many members with bright lines in their spectra, and both have high spatial velocities, especially high for the bright line stars. In both cases the bright lines are ascribed to tenuous outer atmospheres, and for both classes there is a certain amount of direct evidence for the existence of these outer atmospheres. The initial high velocities might be due to the high velocity of (or in) a parent nebula from which the star has come. The subsequent slowing down might be due to the obstruction met with by the condensing star and its extensive envelope in its passage through the universe. That the slowing down is found as we pass along the spectral sequence may be seen if we take, for instance, the radial velocities of the stars showing fixed calcium lines (and, therefore, probably connected with an extensive envelope); we find † on taking out the solar motion that the average residual velocity of 20 stars of types O5 to O7 is 33·8 km./sec., while the average residual velocity of 29 stars of types O8 to B2 is only 21·3 km./sec. The change in velocity is so marked for only a comparatively slight change of spectrum that Campbell's corresponding figure for the B stars, 6·5 km./sec.‡, does not seem to represent an unnatural break in the sequence of velocities, and we may regard the sequence O, B, A as a true physical sequence for early type giants and one which represents a possible line of evolution.

Accepting Eddington's view that most stars are in radiative equilibrium, and that evolution may be shown by a

* J. S. Plaskett, *Pub. D.A.O.*, ii. 287, 1924.

† *Ibid.*, 336, 1924.

‡ "Stellar Motions," p. 209, 1913.

sequence of stars of diminishing mass we come back to a blend of the two historic theories of stellar evolution. For the early type stars we look to the sequence O-B-A, presumably following with F, G, K, etc., and we derive our stars from condensing nebulosity, possibly passing through the planetary nebular stage, P. The dissipation of the nebular envelope follows the condensation of the nucleus, under the intense radiation pressure set up as the nucleus grows in mass, luminosity, and temperature. The subsequent diminution of the mass of the star, which accompanies its decrease in luminosity and temperature, may be due, in part, to the internal destruction of mass and in part to the expulsion of matter from the surface under radiation pressure. It may be conjectured that stars of this early type are formed from the condensation of diffuse nebulosity.

For the late type giants, we look to the sequence M-K-G-F or N-R-G-F as representing possibly the early stages, while the star is reaching a condition of radiative equilibrium, the subsequent development being back along the sequence of diminishing mass luminosity and temperature to the dwarf M stage. It is possible that the red giant stars come from the nuclei which form in the arms of spiral nebulae. They are, in general, less massive than the O, B stars, but they are of the right order of mass for condensations in an outflowing arm of a rotating spiral nebula.* The nuclei would vary in mass, and many of the smaller stars might reach the stage of radiative equilibrium without ever passing through a giant stage at all. All stars alike, once they have reached this stage of equilibrium, would probably evolve along the sequence determined by diminishing mass.

To sum up the views advanced above, the evidence points to two sets of massive stars in an early stage of

* Jeans, "Problems in Cosmogony," p. 219, 1919.

evolution. Two separate sources are indicated, namely, diffuse nebulosity and spiral nebulae. It is suggested that planetary nebulae, O and B type giants come from diffuse nebulosity, while M and N giants come from condensations in the arms of spiral nebulae.

85. The Solar System.—Laplace's Nebular Hypothesis must be our starting-point for any discussion of the cosmogony of the solar system. Starting from a rotating mass of hot gas, Laplace assumed the mass to shrink inwards under the influence of gravitation. Constancy of angular momentum involved an increase in rotational velocity, with consequent instability in the external equatorial regions. The outer ring of matter broke off from the main body and subsequently agglomerated round some nucleus in it to form a planet. A succession of such epochs of instability led to the formation of successive annuli and, later, planets. Laplace's famous hypothesis has been subjected to many attacks, most of which have been shown, on further investigation, not to rule out the possibility of its truth. It seems certain, however, that the scheme of development must be very much modified in detail, if it is to stand. For instance, considerations of angular momentum and of density show that the ejected matter would have to liquefy shortly after ejection, the planets being born in a liquid or even solid state.* This is not impossible, but there is another difficulty which is inherent in the theory. Carrying out the process of equatorial disintegration with its implications as to density and rotational velocity, we ought to reach a stage where the central body should break up by fission into a double star. There is no evidence of this, and it does not seem possible that our solar system can be the result of a break-up of a primitive gaseous mass owing to mere rotational instability.

Some external body is required, to break off from our

* Jeans, "Problems in Cosmogony," Ch. XII.

central sun detached bodies of the size of the planets. Close passages of individual stars are too rare now to make this hypothesis satisfactory, unless we follow Jeans in his theory of closer packing of the stars in an earlier epoch, an idea developed on quite other grounds. Then we may assume the order of events to have been somewhat thus. As the tide-generating star came near the sun instability was set up, resulting in the tidal ejection of matter from the sun's equator, the matter streaming out in one or two jets. The jets would lie approximately in the plane of passage of the disturbing star, and if two jets were formed they would be diametrically opposite to each other. The rate of ejection of matter would be slow at first, increase to a maximum as the star passed close to the sun, and then decrease again. The filament would lose heat rapidly, especially at the ends, would liquefy there most rapidly and would condense into smaller planets at the two ends and into larger masses near the middle. Thus it comes about on this hypothesis that Jupiter and Saturn are so much larger than the inner or outer planets. The planets would describe orbits round the sun, probably at first of fairly large eccentricities, and the satellites of some of the planets might be formed from them as they passed near the sun by the very same kind of tidal force as that which had torn the planets themselves out of the primary central mass. One result of the resisting medium surrounding the sun through which they passed at first would be to diminish the eccentricities of their orbits to the present low values. There are naturally many problems not resolved by this provisional solution of Jeans, but there is much that is attractive in its combination of tidal and rotational effects.

It is not without interest to note the fate of the earlier attempts at cosmogony in the light of Jeans's most recent work. Rotational instability suggested by Laplace and Roche as operative in forming the solar system is found to

apply in modified form, in the building up of stellar systems from gaseous nebulae through the development of spiral forms. Fission and tidal reactions developed by Darwin for the earth-moon system are found to explain the genesis of binary and multiple star systems. The genesis of the solar system and the earth-moon system remain unexplained. But, whereas Darwin clearly thought that tidal forces cannot have been very important in moulding the solar system, Jeans gives them a very important and, in fact, decisive rôle ; only he adds the hypothesis of an external disturbing star passing near in an epoch when stars were more closely packed than at present. One fact emerges clearly. The time for final conclusions in cosmogony has not yet come. The fresh knowledge that crowds in on us on the observational side, especially from the great telescopes of the Pacific coast, may lead to a new set of solutions of the problems of cosmogony within the next century which will differ from those offered by present-day writers as widely as their solutions differ from those of Laplace.

APPENDIX I

TABLE OF LINES DESIGNATED BY LETTERS BY FRAUNHOFER AND OTHERS

Letter.	Wave-length (Rowland) Unless Otherwise Stated.	Chemical Origin.	Authority for Letter.
[Y]	8987.449 I.A. (head of [Y] band)	Atmosphere	Ab.
[x ₄]	8806.730 I.A.	<i>Mg</i>	Ab.
[x ₃]	8662.101 I.A.	<i>Fe—Ca</i>	Ab.
[x ₂]	8542.077 I.A.	<i>Ca</i>	Ab.
[x ₁]	8498.023 I.A.	<i>Ca</i>	Ab.
[Z]	8226.957 I.A.	Atmosphere	Ab.
[A]	7593.709 I.A. (head of [A] band)	Atmosphere	Fr.
[a]	7164.725 (head of [a] group)	Atmosphere	B.P.
[B]	6867.457 (head of [B] group)	Atmosphere	Fr.
[C]	6563.045	<i>Hα</i>	Fr.
[D ₁]	5896.357	}	}
[D ₂]	5890.186		
[D ₃]	5875.618 I.A.	<i>He</i>	—
[E]	5269.723	<i>Fe</i>	Fr.
[b ₁]	5183.791	<i>Mg</i>	}
[b ₂]	5172.856	<i>Mg</i>	
[b ₃]	5169.220 069)	<i>Fe</i>	
[b ₄]	5167.497	<i>Mg</i>	}
[F]	4861.527	<i>Hβ</i>	
[d]	4383.720	<i>Fe</i>	B.P.
[G]	{ 4308.081 4307.907	{ <i>Fe</i> <i>Ca</i> }	Fr.
[g]	4226.904	<i>Ca</i>	B.P.
[h]	4102.000	<i>Hδ</i>	B.P.
[i]	4045.975	<i>Fe</i>	B.P.
[H]	3968.625	<i>Ca</i>	Fr.

TABLE—Continued

Letter.	Wave-length (Rowland) Unless Otherwise Stated.	Chemical Origin.	Authority for Letter.
[K]	3933·825	Ca	Ma.
[L]	3820·586	Fe—C	Be.
[M]	3727·778	Fe	Be.
[N]	3581·349	Fe	Be.
[O]	3440·762 } 1·135 }	Fe } Fe }	Be.
[P]	3361·327	Ti	Be.
[Q]	3286·898	Fe	Es.
[R]	3179·453	Ca, Cr	Es.
[r]	3143·879	Ti	Ma.
[S]	3100·001	Fe	Ma.
	(head of group)		
[s]	3046·778	Ti	Co.
[T]	3021·170	Fe	Ma.
[t]	2994·527	Fe	Co.
[U]	2947·99	Fe	Co.

Authorities.—Fraunhofer (Fr.), *Denkschrift. der K. Akad. de Wiss. zu München*, v. 193, 1814; Baden Powell (B.P.), *British Association Report*, 1839; Becquerel (Be.) *Bibliothèque Universelle de Genève*, xl. 351, 1842; Esselbach (Es.) *Annalen der Physik*, xcvi. 513, 1856; Mascart (Ma.) *Annales Scientifiques de l'Ecole Normale Polytechnique* i. 237, 1864; Abney (Ab.) *Phil. Trans.*, clxxvii. 653, 1880; Cornu (Co.), *Spectre Normal du Soleil*, 1881.

It should be noted that different writers have adopted the same letters for different lines, and some of the above identifications are open to doubt. Thus at the infra red end Langley (*Annals of Astrophysical Observatory of Smithsonian Institution*, i. 1900) has used the symbols [X] [Y] for lines different from those of J. W. Draper (*Phil. Mag.*, xxii. 362, 1843) or of Abney, while Higgs (*R.S. Proc.*, liv. 200, 1893) described an [a] band of oxygen at $\lambda 6276\cdot7$, which is different from Draper's [a] though it may be the same as that of Brewster (*Phil. Trans.*, cl. 149, 1860). At the other end of the spectrum, Esselbach has a different set of identifications for the lines [L] [M] [N] [O] [P] [Q] and [R] from those which have been generally adopted. Again, Baden Powell's lines [c] [d] [e] have not been identified definitely, though $\lambda 4383\cdot720$, Fe, has been allotted

the letter [d]. Baden Powell's original [f] is now the line universally known as [g]. The lines [H] and [K] were formerly known as [H₁] and [H₂] respectively or as [H] and [k]. Rowland's identification of Fraunhofer's [G] line with an iron and calcium pair must be supplemented by an identification with elements of a hydrocarbon band (Newall, Baxandall, and Butler, *M.N.R.A.S.*, lxxvi. 640, 1916).

APPENDIX II

REDUCTION OF PRISMATIC SPECTROGRAMS

Let n_1, n_2, n_3 be the measured scale-readings for three lines of known wave-lengths $\lambda_1, \lambda_2, \lambda_3$. It is required to determine the constants λ_0, c, n_0 of the reduction formula $\lambda = \lambda_0 + \frac{c}{n - n_0}$.

The following tabular presentation of the calculation involved I owe to Professor Newall. The successive sets of figures of the actual work are represented by numbers enclosed in brackets. We take $\lambda_1 < \lambda_2 < \lambda_3$.

(1) = λ_1		(6) = n_1	
	(4) = $\lambda_2 - \lambda_1$		(9) = $n_2 - n_1$
(2) = λ_2		(7) = n_2	
	(5) = $\lambda_3 - \lambda_2$		(10) = $n_3 - n_2$
(3) = λ_3		(8) = n_3	
(11) = $\frac{(4)}{(9)}$	(13) = $\frac{(11)}{(12)}$	(15) = (6) \times (13)	
(12) = $\frac{(5)}{(10)}$	(14) = 1 - (13)	(16) = (8) - (15)	(17) = $\frac{(16)}{(14)} = n_0$
(20) = (17) - (8)	(21) = λ_1	(18) = (17) - (6)	
	(22) = (11) \times (19)	(19) = (17) - (7)	
	(23) = (21) - (22) = λ_0	(24) = (22) \times (18) = c	
	(25) = $\frac{(24)}{(20)}$		
	(26) = (25) + (23) = λ_3 .		

The agreement of (26) with λ_3 provides the check on the computation.

An actual reduction of a spectrogram is added by way of illustration.

$$\begin{aligned}
 \lambda_1 = (1) &= 4202.033 & n_1 = (6) &= 35.2551 \\
 &(4) 92.097 & &(9) 15.8343 \\
 \lambda_2 = (2) &= 4294.130 & n_2 = (7) &= 51.0894 \\
 &(5) 89.420 & &(10) 13.3023 \\
 \lambda_3 = (3) &= 4383.550 & n_3 = (8) &= 64.3917 \\
 &(11) 5.816297 & (13) 0.865244 & (15) 30.5043 \\
 &(12) 6.722130 & (14) 0.134756 & (16) 33.8874 & n_0 = (17) = 251.4722 \\
 & & & & &(18) 216.2171 \\
 &(20) 187.0805 & (21) 4202.033 & & &(19) 200.3828 \\
 & & (22) 1165.486 & & & c = (24) = 251998.0 \\
 & & & & & \\
 \lambda_0 = (23) &= 3036.547 & & & & \\
 &(25) 1347.003 & & & & \\
 &(26) 4383.550 & = \lambda_3. & & &
 \end{aligned}$$

APPENDIX III

TABLE (a)

TABLE OF CORRECTIONS TO REDUCE WAVE-LENGTHS FROM
ROWLAND'S SYSTEM TO THE INTERNATIONAL SYSTEM

Wave-Lengths.	Correction.	Wave-Lengths.	Correction.
2950-3125	- 0.12	5375-5400	- 0.20
3125-3250	- 0.13	5400-5500	- 0.21
3250-3450	- 0.14	5500-6050	- 0.22
3450-4150	- 0.15	6050-6500	- 0.21
4150-4350	- 0.16	6500-6570	- 0.22
4350-4550	- 0.17	6570-6750	- 0.23
4550-5125	- 0.18	6750-6850	- 0.24
5125-5300	- 0.17	6850-7000	- 0.25
5300-5325	- 0.18	7000-7200	- 0.26
5325-5375	- 0.19	7200-7400	- 0.27

TABLE (b)

TABLE OF CORRECTIONS TO BE APPLIED TO WAVE-LENGTHS IN AIR
AT 15° C. AND 760 MM. TO REDUCE TO VALUES *in vacuo*

(Meggers and Peters, *Ap. J.*, 1. 61, 1919)

λ.	Add.	λ.	Add.	λ.	Add.
2000	0.6512	2250	0.6993	2500	0.7535
2050	0.6601	2300	0.7097	2550	0.7649
2100	0.6695	2350	0.7204	2600	0.7764
2150	0.6791	2400	0.7313	2650	0.7880
2200	0.6891	2450	0.7423	2700	0.7997

TABLE (b)—Continued

λ .	Add.	λ .	Add.	λ .	Add.
2750	0·8115	4500	1·2581	6250	1·7251
2800	0·8235	4550	1·2713	6300	1·7386
2850	0·8355	4600	1·2845	6350	1·7520
2900	0·8476	4650	1·2978	6400	1·7655
2950	0·8598	4700	1·3110	6450	1·7789
3000	0·8721	4750	1·3242	6500	1·7924
3050	0·8844	4800	1·3375	6550	1·8058
3100	0·8968	4850	1·3508	6600	1·8193
3150	0·9092	4900	1·3640	6650	1·8328
3200	0·9217	4950	1·3773	6700	1·8462
3250	0·9343	5000	1·3906	6750	1·8597
3300	0·9469	5050	1·4039	6800	1·8732
3350	0·9595	5100	1·4173	6850	1·8866
3400	0·9722	5150	1·4306	6900	1·9001
3450	0·9849	5200	1·4439	6950	1·9136
3500	0·9977	5250	1·4572	7000	1·9271
3550	1·0104	5300	1·4706	7050	1·9406
3600	1·0233	5350	1·4839	7100	1·9541
3650	1·0361	5400	1·4973	7150	1·9676
3700	1·0490	5450	1·5106	7200	1·9811
3750	1·0619	5500	1·5240	7250	1·9945
3800	1·0749	5550	1·5374	7300	2·0080
3850	1·0878	5600	1·5508	7350	2·0215
3900	1·1008	5650	1·5642	7400	2·0350
3950	1·1138	5700	1·5775	7450	2·0485
4000	1·1268	5750	1·5909	7500	2·0620
4050	1·1399	5800	1·6043	7550	2·0756
4100	1·1530	5850	1·6177	7600	2·0891
4150	1·1661	5900	1·6311	7650	2·1026
4200	1·1792	5950	1·6446	7700	2·1161
4250	1·1923	6000	1·6580	7750	2·1296
4300	1·2054	6050	1·6714	7800	2·1431
4350	1·2186	6100	1·6848	7850	2·1566
4400	1·2317	6150	1·6983	7900	2·1702
4450	1·2449	6200	1·7118	7950	2·1837

TABLE (b)—Continued

λ	Add.	λ	Add.	λ	Add.
8000	2.1972	8500	2.3325	9250	2.5357
8050	2.2107	8550	2.3460	9300	2.5492
8100	2.2243	8600	2.3596	9350	2.5628
8150	2.2378	8650	2.3731	9400	2.5763
8200	2.2513	8700	2.3867	9450	2.5899
8250	2.2648	8750	2.4002	9500	2.6035
8300	2.2784	8800	2.4137	9550	2.6170
8350	2.2919	8850	2.4273	9600	2.6306
8400	2.3054	8900	2.4408	9650	2.6441
8450	2.3190	8950	2.4544	9700	2.6577
		9000	2.4679	9750	2.6713
		9050	2.4815	9800	2.6848
		9100	2.4950	9850	2.6984
		9150	2.5086	9900	2.7119
		9200	2.5221	9950	2.7255
				10000	2.7391

SUGGESTED LINES FOR ADOPTION AS SECONDARY STANDARDS
WHEN FULLY OBSERVED

(a) Stable Iron Lines

2375·193	2632·248	2912·161	3155·293
2380·763	2641·654	2926·584	3161·370
2389·979	2656·154	2941·343	3171·353
2399·244	2669·498	2959·996	3184·903
2406·663	2679·066	2976·130	3191·666
2413·313	2699·498	2987·293	3202·562
2443·871	2714·419	2990·394	3217·389
2453·478	2728·026	3011·484	3233·061
2468·885	2746·486	3024·035	3246·015
2474·818	2759·816	3030·150	3265·057
2496·539	2778·847	3040·430	3268·246
2507·904	2797·777	3045·082	3280·268
2512·366	2813·288	3055·268	3292·029
2524·291	2817·506	3068·180	3298·137
2535·610	2828·808	3078·436	3314·746
2543·927	2848·714	3083·745	3317·126
2549·616	2851·798	3091·581	3323·741
2566·921	2858·898	3098·191	3325·468
2584·544	2866·629	3116·632	3337·671
2598·380	2874·176	3125·663	
2612·787	2887·808	3129·334	
2621·677	2899·418	3142·888	

(b) Iodine Lines

5167·478	5364·866	5410·923	5455·623
5171·594	5371·478	5410·955	5497·506
5227·187	5393·157	5415·190	5506·768
5232·908	5393·183	5424·052	5572·860
5266·563	5397·157	5429·726	5586·752
5266·583	5404·150	5434·527	
5324·179	5405·787	5446·936	

APPENDIX V

TERTIARY STANDARDS, INTERNATIONAL SYSTEM, IN THE ARC SPECTRUM OF IRON

3379·023	3581·196	3704·464	3790·096
3380·115	3582·202	3705·568	3794·342
3392·657	3584·664	3707·050	3795·005
3396·981	3585·321	3711·226	3797·518
3401·523	3586·115	3715·915	3798·514
3402·262	3589·108	3719·936	3799·550
3407·463	3594·634	3722·565	3806·702
3413·136	3603·207	3727·622	3867·541
3417·845	3608·862	3732·400	3808·732
3418·511	3617·789	3733·320	3814·527
3424·289	3618·770	3734·868	3815·843
3427·122	3621·464	3737·134	3821·182
3447·282	3623·188	3738·309	3824·445
3450·332	3625·149	3742·623	3825·885
3458·306	3630·352	3745·564	3827·826
3465·864	3631·465	3745·903	3833·313
3476·707	3632·041	3748·265	3834·226
3489·673	3638·300	3749·488	3839·260
3495·291	3645·825	3756·942	3840·440
3497·110	3647·845	3758·236	3841·052
3497·845	3649·509	3760·053	3846·805
3506·501	3651·470	3763·791	3849·970
3521·265	3659·520	3765·544	3852·577
3529·821	3669·524	3767·195	3856·373
3541·088	3679·916	3774·827	3859·914
3542·080	3684·112	3776·457	3867·220
3545·642	3687·459	3781·190	3871·752
3558·519*	3690·731	3785·950	3872·505
3565·382	3695·054	3786·680	3873·764
3576·761*	3702·034	3787·884	3878·022

* Lines selected to replace unsatisfactory secondary standards (see Appendix IV) as soon as measures of the proper accuracy are available.

APPENDIX V—*Continued*

3878·575	4009·718	4213·652	4454·386
3883·284	4014·536	4216·188	4459·124
3884·362	4031·966	4219·367*	4461·657
3886·285	4044·616	4226·426	4476·024
3887·052	4045·818	4245·261*	4489·745
3888·518	4062·448	4250·792	4490·088
3895·659	4066·981	4266·970	4514·193
3899·710	4067·277	4267·832	4517·532
3902·949	4067·985	4271·766	4528·622
3903·903	4074·792*	4285·449	4587·136
3910·848	4085·011	4294·130	4602·008
3917·186	4095·977*	4298·043	4619·297
3920·261	4098·185	4305·457	4630·128
3922·915	4100·743	4307·909	4632·918
3925·947	4107·495*	4325·766	4638·019
3927·923	4109·809	4327·101	4654·504
3930·300	4114·451	4337·052	4667·461
3932·631	4120·212	4346·561	4673·171
3937·332	4121·808	4351·552	4678·856
3940·884	4122·523	4358·507	4710·288*
3942·444	4127·614	4367·583	4733·598*
3948·780	4132·062	4369·777	4741·535*
3952·606	4132·905	4383·550	4745·808
3956·461	4137·003	4387·899	4772·818
3956·682	4143·421	4390·956	4786·812
3966·067	4143·873	4404·754	4788·762
3967·424	4154·504	4407·716	4802·886
3969·262	4156·805*	4408·421	4924·776*
3971·327	4170·908	4415·128	4939·691*
3981·776	4175·642*	4422·373	4994·135*
3983·962	4177·599	4430·621	5041·076*
3986·177	4181·761	4435·154	5041·760
3990·380	4184·897*	4442·346	5051·639
3997·397	4202·033	4443·199	5098·706
4005·248	4203·988*	4447·724	5123·725*

* Lines selected to replace unsatisfactory secondary standards (see Appendix IV) as soon as measures of the proper accuracy are available.

APPENDIX V

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APPENDIX V—Continued

5127·365	5424·038	5984·796	6200·323
5150·845*	5429·701	5987·050	6213·437
5151·916	5445·039*	6003·051	6215·150
5166·288	5446·921	6007·961	6219·290
5168·903	5462·959	6008·595	6232·669
5171·601	5463·268	6013·528	6246·350
5198·715*	5473·917	6016·668	6252·567
5202·340*	5476·295	6020·178	6254·267
5216·280*	5476·587	6021·830	6280·623
5227·193	5501·470	6024·051	6297·803
5242·406*	5535·419	6042·083	6301·531
5250·652*	5543·173	6055·983	6302·520
5269·540	5543·944	6078·470	6315·310
5270·360*	5554·872	6089·571	6322·696
5307·365*	5563·613	6102·179	6336·851
5328·537*	5565·688	6103·183	6344·161
5332·903	5572·859	6127·915	6355·040
5341·028*	5576·109	6136·624	6380·753
5378·588	5598·279	6136·998	6400·026
5383·353	5602·958	6147·844	6408·044
5393·188	5624·559	6151·636	6411·678
5397·134	5638·275	6157·734	6421·362
5400·507	5975·354	6165·368	6462·738
5410·890	5976·816	6173·344	6475·639
5415·175	5983·712	6180·225	6518·382
			6575·029
			6609·125
			6663·455

* Lines selected to replace unsatisfactory secondary standards (see Appendix IV) as soon as measures of the proper accuracy are available.

APPENDIX VI

WAVE-LENGTHS OF LINES OF BALMER'S SERIES

(Extracted from "Report on Series in Line Spectra," A. Fowler,
Physical Society of London, 1922)

	Wave-lengths I.A. Units (Air at 15° C. and 760 mm.).		Wave-lengths I.A. Units (Air at 15° C. and 760 mm.).
H _a	6562.793	H _π	3697.154
H _β	4861.327	H _ρ	91.557
H _γ	4340.466	H _σ	86.834
H _δ	4101.738	H _τ	82.810
H _ε	3970.075	H _υ	79.355
H _ζ	3889.052	H _φ	76.365
H _η	3835.387	H _ψ	73.731
H _θ	3797.900	H _χ	71.478
H _ι	70.633	H _ω	69.466
H _κ	50.154	26	67.684
H _λ	34.371	27	66.097
H _μ	21.941	28	64.679
H _ν	11.973	29	63.405
H _ο	03.855	30	62.258
		∞	45.981

APPENDIX VII

WOLFER'S TABLE OF SUN-SPOT MAXIMA AND MINIMA*

Minima.	Maxima.	Minima.	Maxima.
1610·8	1615·5	1766·5	1769·7
1619·0	1625·0	1775·5	1778·4
1634·0	1639·5	1784·7	1788·1
1645·0	1649·0	1798·3	1805·2
1655·0	1660·0	1810·6	1816·4
1666·0	1675·0	1823·3	1829·9
1679·5	1685·0	1833·9	1837·2
1689·5	1693·0	1843·5	1848·1
1698·0	1705·5	1856·0	1860·1
1712·0	1718·2	1867·2	1870·6
1723·5	1727·5	1878·9	1883·9
1734·0	1738·7	<u>1889·6</u>	<u>1894·1</u>
1745·0	1750·3	1901·7	1906·4
1755·2	1761·5	1913·4	1917·6

* *V.J.S. der Naturforschenden Gesellschaft in Zurich*, xlvii, 240, 1902.

APPENDIX VIII

IMPORTANT LINES OF UNKNOWN ORIGIN IN VARIOUS CELESTIAL SPECTRA

The particular spectrum to which any line belongs is denoted by X.
 The letters in brackets denote the references to the records drawn on.

Wave-length (I. A.).	(a)	(b)	(c)	(d)	(e) (f)		(g)	(h)	(i)	(j)	(k)	(l)	(s)
	Fraunhofer Spectrum.	Chromosphere.	Corona.	Nebulæ.	Dark Lines.	Wolf-Rayet Stars.	Novæ (Later Stages).	<i>η Carinae</i> .	Me Stars (Bright Lines).	Various Individual Stars.	Aurora.		
3208·1													
3313					X								
3328													
3342				X	X								
3346				X	X								
3388			X										
3426·2				X									
3432·5				X									
3445				X									
3455			X										
3601·1			X										
3611													
3626			X										
3641·2			X										
3643			X										
3648			X										
3726·16				X									
3728·91				X									
3759				X									
3800·8			X										X

APPENDIX VIII—Continued

Wave-length (I. A.).	(a)	(b)	(c)	(d)	(e) (f)		(g)	(h)	(i)	(j)	(k)	(l)	(s)
	Fraunhofer Spectrum.	Chromosphere.	Corona.	Nebulæ.	Dark Lines.	Bright Lines.	Novæ (Later Stages).	Wolf-Rayet Stars.	<i>η Carinæ.</i>	Me Stars (Bright Lines).	Various Individual Stars.	Aurora.	
3840.2				X									
3860													
3868.74				X								(p) (m)	
3883					(f)								
3907.26													
3911.2										(j)			
3932.54										(j)	(n)		
3938.19										(j)			
3938.40	X	X								(j)			
3945.0											(m)		
3952.1		X									(m)		
3954.1											(p)		
3965.3					(e)								
3967.51				X									
3967.58										(j)			
3983.8													
3986.7			X								(l) (o)		
4006.82										(j)			
4021.4		X											
4022					(f)						(m)		
4024.4													
4025.13					(e)								
4038											(l)		
4050.7					(f)								
4056.5						X							
4063.6					(f)								
4067.92					(e)								
4068.62				X									
4069.5											(q)		
4070						X							
4075.9											(l) (p)		

APPENDIX VIII—Continued

Wave-length (I.A.).	(a)	(b)	(c)	(d)	(e) (f)		(g)	(h)	(i)	(j)	(k)	(l)	(r)	(s)
	Fraunhofer Spectrum.	Chromosphere.	Corona.	Nebulæ.	Dark Lines.	Bright Lines.	Novæ (Later Stages).	<i>η Carinae</i> .	Me Stars (Bright Lines).	Various Individual Stars.	Aurora.			
4076.22	—	—	—	X	—	—	—	—	—	—	—	—	—	—
4084.5	—	—	—	—	(f)	—	—	—	—	—	—	—	—	—
4085.2	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4085.8	—	—	X	—	—	—	—	—	—	—	—	—	—	—
4086.5	—	X	—	—	—	—	—	—	—	—	—	—	—	—
4091.6	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4099.22	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4122.7	—	X	—	—	—	—	—	—	—	—	—	(n)	(m)	—
4128.7	—	—	—	—	—	—	—	—	—	—	—	(p)	—	—
4132.3	—	—	—	—	—	—	—	—	—	—	—	(q)	—	—
4137.3	—	X	—	—	—	—	—	—	—	—	—	—	—	—
4138.65	—	—	—	—	—	—	—	—	(k)	—	—	—	—	—
4152.84	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4155.2	—	—	—	—	—	X	—	—	—	—	—	—	—	—
4156.51	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4159.19	X	—	—	—	—	—	—	—	—	—	—	—	—	—
4162.94	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4163.6	—	—	—	—	—	X	—	—	—	—	—	—	—	—
4178.82	—	—	—	—	—	—	—	—	—	(k)	—	—	—	—
4182.3	—	—	—	—	—	—	—	—	—	—	—	—	—	X
4184.00	X	—	—	—	—	—	—	—	—	—	—	—	—	—
4186.93	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4188.73	X	—	—	—	—	—	—	—	—	—	—	—	—	—
4191.6	—	—	—	—	—	—	—	—	—	—	—	(p)	—	—
4198.24	X	—	—	—	—	—	—	—	—	—	—	—	—	—
4212.33	—	—	—	—	(e)	—	—	—	—	—	—	—	—	—
4215.74	—	—	—	—	—	—	—	—	(k)	—	—	—	—	—
4231.2	—	—	X	—	—	—	—	—	—	—	—	—	—	—
4233.35	—	—	—	—	—	—	—	—	(k)	—	—	—	—	—
4241	—	—	X	—	—	—	—	—	—	—	—	—	—	—
4244.09	—	—	—	—	—	—	—	X	—	—	—	—	—	—

APPENDIX VIII—Continued

Wave-length (I.A.).	Fraunhofer Spectrum.	(a)	(b)	(c)	(d)	(e) (f)		(g) (h)	(i)	(j) (k)	(l) to (r)	(s)
						Dark Lines.	Wolf-Rayet Stars. Bright Lines.					
4244.6	—	—	—	X	—	—	—	—	—	—	—	—
4258.4	—	—	—	—	—	—	—	—	—	—	—	—
4273.4	—	—	—	—	—	—	—	—	—	—	—	—
4275.4	—	—	—	—	—	—	—	—	—	—	—	—
4275.86	—	—	—	—	—	(e)	—	—	—	—	—	—
4276.85	—	—	—	—	—	—	—	—	X	—	—	—
4287.29	—	—	—	—	—	—	—	—	X	—	—	—
4301.10	X	—	—	—	—	—	—	—	—	—	—	—
4303.94	X	—	—	—	—	—	—	—	—	—	—	—
4311	—	—	—	X	—	—	—	—	—	—	—	—
4320.4	—	—	—	—	—	(f)	—	—	—	—	—	—
4325.6	—	—	—	—	—	—	X	—	—	—	—	—
4358.94	—	—	—	—	—	—	—	—	X	—	—	—
4359.3	—	—	—	X	—	—	—	—	—	—	—	—
4363.20	—	—	—	—	X	—	—	—	—	—	—	—
4372.7	—	—	—	—	—	—	—	—	—	(j) (k)	—	—
4376.8	—	—	—	—	—	—	—	—	—	—	(p)	—
4391.6	—	—	—	—	—	(e)	—	—	—	—	—	—
4413.87	—	—	—	—	—	—	—	—	X	—	—	—
4416.26	—	—	—	—	—	—	—	—	X	—	—	—
4441.2	—	—	—	—	—	—	X	—	—	—	—	—
4446.38	—	X	—	—	—	—	—	—	—	—	—	—
4448	—	—	—	—	—	—	—	—	X	—	(l)	—
4448.13	—	—	—	—	—	—	—	—	—	(j)	—	—
4456.8	—	—	—	—	—	—	X	—	—	—	—	—
4457.80	—	—	—	—	—	—	—	—	X	—	—	—
4458.83	—	—	—	—	—	—	—	—	—	(k)	—	—
4462.1	—	X	—	—	—	—	—	—	—	—	—	—
4465.6	—	—	—	—	—	(f)	—	—	—	—	—	—
4474.70	—	—	—	—	—	—	—	—	X	—	—	—
4511.46	—	—	—	—	—	—	—	—	—	(k)	—	—

APPENDIX VIII—Continued

Wave-length (I.A.).	(a) Fraunhofer Spectrum.	(b) Chromosphere.	(c) Corona.	(d) Nebulæ.	(e) (f) Wolf-Rayet Stars.		(g) Novæ (Later Stages).	(h) <i>η Carinæ</i> .	(i) Me Stars (Bright Lines).	(l) Various Individual Stars.	(r) Aurora.
					Dark Lines.	Bright Lines.					
4814.60											
4889.46											
4958.91				X							
5006.84				X							
5073			X								
5118			X								
51307											
5250.9						X					
5284.11		X									
5302.9			X								
5325.57		X									
5425.25		X									
5536			X								
5578.0											
5737				X							X
5755				X							
5919.19					(e)						
6278.33					(e)						
6302				X							
6313				X							
6364				X							
6374.3			X								
6548.1				X							
6558.25					(e)						
6583.6				X							
6730				X							
7009				X							
7138				X							
7325				X							

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