AN
OUTLINE
OF
STELLAR
ASTRONOMY

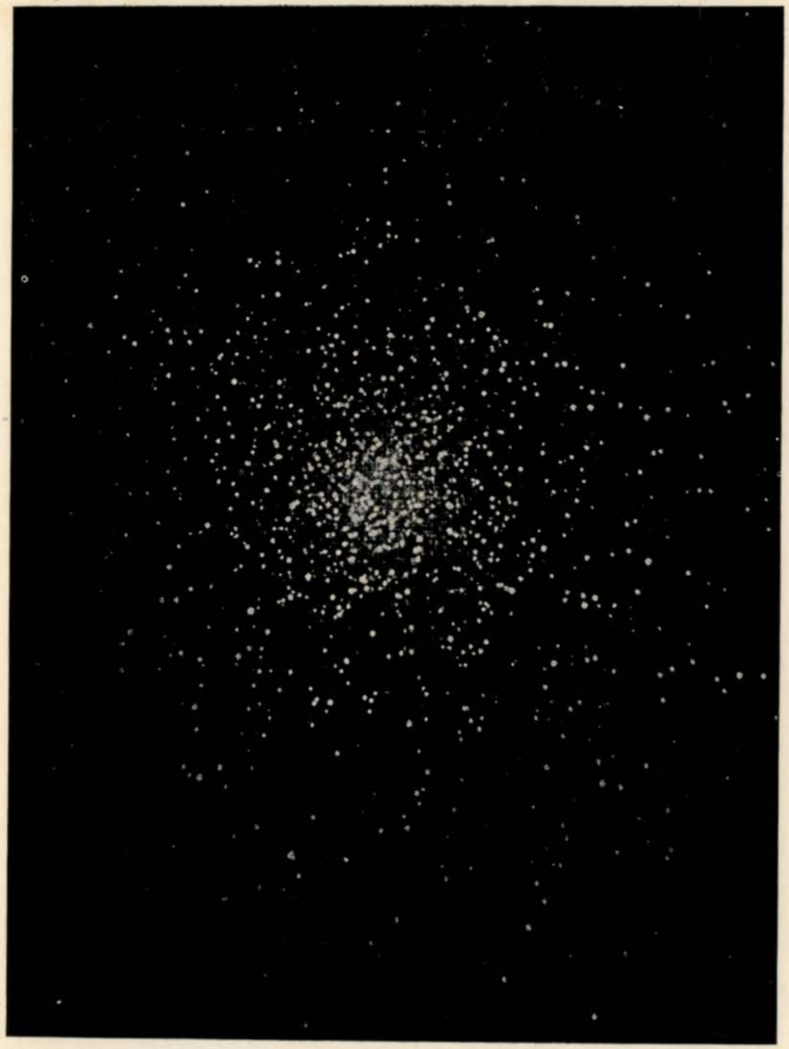
•

PETER
DOIG,
F.R.A.S.

HUTCHINSON'S
SCIENTIFIC

AN OUTLINE OF STELLAR ASTRONOMY

First published - - - - - 1927
Second Edition, completely revised - 1947



THE GLOBULAR CLUSTER IN HERCULES, M13, NGC 6205.

(Relatively short time of exposure, 72-in. reflector, with central region therefore not over-exposed).

AN OUTLINE OF STELLAR ASTRONOMY

BY

PETER DOIG, F.R.A.S.

HUTCHINSON'S SCIENTIFIC AND TECHNICAL PUBLICATIONS

LONDON, NEW YORK, MELBOURNE, SYDNEY, CAPE TOWN

CONTENTS

TABLES

APPENDICES

INTRODUCTORY

THIS book gives an outline of the state of knowledge of the constitution, dimensions, motions and distribution in space of the stars and nebulae.

The advance to an unexpected degree in ascertainment of the distances and disposition throughout the Universe of the stars, during the past two or three generations, can perhaps not be better illustrated than by a quotation from a book by the well-known astronomical writer, R. A. Proctor, published seventy years ago. By no means a pessimist as regards the progress of scientific discovery he nevertheless wrote as follows :—"Even the mighty instruments of our own day, wielded with all the skill and acumen which a long experience has generated, have not sufficed to enable us to measure the distance of more than about a dozen stars. Nor probably will it ever be possible for man to count by the hundred the number of stars whose distances are known. The real architecture of the stellar system must remain for ever unknown to us, except as respects a relatively minute portion, lying within certain limits of distances from the Earth." ("Our Place among Infinities," p. 188, 1875).*

In this book the extent to which the above views have become far from correct, owing to great improvement in old methods and development of new means for estimating celestial distances, will be made evident.†

The new ideas which are partly the consequence of these advances, and partly the sequel to revolutionary discoveries in physical science, make it difficult for even the most assiduous to follow progress. In order, therefore, to give the student an idea of the places in which he may expect to find the results of investigations and also to help him in studying more thoroughly the work of the past, a short bibliographical note is appended to each chapter.

At the outset it is desirable to give brief definitions of the chief terms used, leaving to an appendix more technical questions of

* And in a lecture delivered in the 'sixties of last century, Sir John Herschel remarked, in connection with recently determined parallaxes of a few stars, that "A stepping-stone is thus laid for another upward struggle towards the infinite—to the nebulae, the remotest objects of which we have any knowledge, though the stride here is too vast, as it may seem, for the limited faculties of man ever to take" ("Familiar Lectures on Scientific Subjects," p. 181, 1867).

† The number of fairly reliable trigonometrical parallaxes (of course, not quite the same thing as well-established distances) has grown as follows :—in 1840, 3 ; 1880, about 20 ; 1900, about 60 ; 1915, nearly 200 ; 1925, close on 2000 ; 1935, nearly 7,500.

derivation and explanation. It is assumed that the reader is familiar with the meaning of the commoner terms such as "trigonometrical parallax," "stellar magnitude," "proper motion," and so forth and also with the main features of stellar spectroscopy.*

In other words, this book is meant for readers with slightly more knowledge than that necessary for perusal of "popular" astronomical literature. But it will be found that no advanced mathematics is involved, all that is essential being an acquaintance with logarithms and with very elementary trigonometry.

Only the chief terms are given in the following paragraphs. Appendix A gives fuller explanations and derivations of formulae.

Absolute magnitude is defined as the apparent stellar magnitude which any celestial object (*e.g.*, star, cluster of stars or nebula) would have if placed at a distance of ten parsecs, the "parsec" being the distance corresponding to a parallax of one second of arc.

Bolometric magnitude is the stellar magnitude corresponding to the total energy radiated, and is a measure of the total intensity in the same way that *visual magnitude* is a measure of luminous intensity, and *photographic magnitude* a measure of photographic intensity, which may be *photovisual* (with yellow light filter), or *red* (with red filter). Bolometric magnitude is so adjusted numerically as to give the same value as visual magnitude in the case of a star of about 6500°K effective temperature. It is consequently nearly the same as visual magnitude in the case of a G0 type star such as the Sun, which has an effective temperature of 5800°K.

Radiometric magnitude is sometimes referred to. It is a measure of the radiation from a star which reaches the earth's surface, the zero being chosen to agree with the visual magnitude of type A0. It differs from bolometric magnitude in this respect, and also from the fact that the earth's atmosphere reflects and absorbs part of a star's radiation.

Effective temperature is "a conventional measure, specifying the rate of outflow of radiant heat per unit area ; it is not to be regarded as the temperature at any particularly significant level in the star" (Eddington).

Colour index is the difference between photographic and visual magnitude, the hotter bluish or white stars having a negative value of this factor, the yellow and red cooler stars having a positive value.

Surface brightness is usually given in stellar magnitudes. It is the measure of average brightness per unit of radiating area, compared with that of the Sun, and it is not to be confused with *Luminosity* which is a measure of the total light received from a star.

* A short glossary of some of these and of other important terms is appended at the end of the book.

Other terms of less frequent occurrence will be explained as they arise.

With regard to *Designation of Nebulae*, there are two systems of nomenclature current. The older is that of the catalogues of Messier (1730-1817) who listed 103 bright clusters and nebulae, mostly found during his comet hunting ; they are referred to by the use of M and a number (for example, the Orion Nebula is M42). The other is by the numbering of the *New General Catalogue* or the *Index Catalogues* of Dreyer (1852-1926) which contain 7840 and 5386 objects respectively ; the letters NGC or IC are used with the appropriate number.

Although the progress of so intricate a subject as stellar astronomy must necessarily be the result of work by trained professional specialists, yet the writer feels that something of minor importance may be achieved in this branch by amateurs, even if they are only acting as sources of suggestion to those better qualified. It is partly in this hope, as well as with the purpose of providing a useful outline of astrophysical knowledge, that these chapters have been written.

An attempt has been made throughout to give concisely by tabular presentation, wherever this is practicable, some of the data from which the theories of astrophysics have been constructed.

For the sake of consistency the unit of distance used throughout is the light year, a unit based on a fundamental physical constant—the velocity of light.

Readers of the first edition of this book will find that this is practically a new work, owing to discoveries of the past twenty years, such as the rotation of the galaxy, the absorption of light by interstellar matter, the establishment of the status as external galaxies of the extragalactic nebulae, and the development of the pulsation theory of stellar variability, all of which are dealt with in the following pages.

The author is indebted to Dr. Martin Davidson, F.R.A.S., who, although not responsible in any way for errors of fact or opinion which may exist in the book, has read the manuscript and made some valuable suggestions.

Part I—The Individual Star—Observational Data

Chapter I

DIMENSIONS, LUMINOSITIES AND MASSES OF THE STARS

ONE of our greatest authorities once remarked that "it does not seem too sanguine to hope that in a not too distant future we shall be able to understand fully so simple a thing as a star." This rather optimistic remark was based on the circumstance that the high temperature matter of which a star is composed is thought to be the simplest kind of substance that a mathematical physicist can study ; simpler than material at terrestrial temperatures which has complex properties certain to be very difficult to deal with. Nevertheless astronomers are not yet agreed on any comprehensive theory, although there are some points upon which there does not seem to be any substantial difference of opinion.

As a necessary preliminary to a description of modern theory, sections giving the data of observation are first submitted, covering as far as possible in the space at disposal the observed results for dimensions, movements, luminosities and other physical properties of individual stars and multiple systems.

The Dimensions of the Stars

In the very earliest times the anthropocentric trend of human thought was displayed in the attribution of small dimensions to the Sun and still smaller sizes to the stars. On the other hand, astronomical distances were underestimated to a yet greater degree, the fixed stars being considered by Tycho Brahe and his sixteenth century contemporaries to show to naked-eye observation diameters of a minute or two of arc, although Hevelius in the seventeenth and Cassini in the early eighteenth century thought they had found a diameter for Sirius of five or six seconds. These were, however, only spurious images formed by small telescope apertures, and were suspected to be such by Horrocks and Halley because of the instantaneous disappearance of stars when occulted by the moon. After unsuccessful attempts at parallax determination it became evident that stellar distances were so great that the apparent angular diameters of the stars could be only a few hundredths of a second of arc, unless stellar dimensions were very much greater than those of the Sun.* That remarkable astronomical theorist, the Rev. John Michell (1725-1793) pointed out in 1767 that even in the case of the brightest star, Sirius, the apparent angular diameter must be less than "the hundredth, probably the two-hundredth part of a second," although he thought that "it is not unreasonable to suspect that very possibly some of the fixed stars may have so little natural brightness in proportion to their magnitude as to admit of their diameters having some sensible apparent size"; and he further considered that this "natural brightness" would be according to colour, the white stars having the brightest surfaces. The largest telescopes having failed to show any sensible disc to the brightest or reddest stars, it became necessary to attack the problem by some method other then that of direct vision.

Each star image on a photograph is a cluster of silver grains which is enormously larger than any real stellar disc. Even if there were a supergiant star like α Herculis (see Table 1) as near to us as the nearest star (α Centauri, 4.3 light years), its real diameter on the scale of a photograph where the moon was six inches in diameter, would be less than a fiftieth of an inch. There is no such large star within a distance many times as great; and as stars are generally much smaller and further away, the true stellar dimensions on photographs are very greatly less. For instance, on the scale of Plate 7b, the brightest fixed star Sirius would be one two-hundred-thousandth of an inch. In fact, it may be shown (see page 27) that if all the stars of our stellar system were concentrated into one stellar disc its size would be less than a two-thousandth of an inch on the scale of the plate mentioned, the area of which plate covers less than a ten-thousandth of the whole sky.

The application of spectrum analysis resulted in schemes of classification by Secchi (1818-1878), Vogel (1842-1907), Norman Lockyer (1836-1920) and E. C. Pickering (1846-1919), which, although arbitrary and empirical, have formed the foundation upon which theories of stellar constitution and evolution have been built. Into the modern Harvard system, now definitely adopted universally, the main features of over 99 per cent. of stellar spectra fall in a continuous linear sequence, O, B, A, F, G, K, M, where O is the Wolf-Rayet, B the helium star, A the Sirian, F the type of Canopus, G the Capellan, K the Arcturian and M the red stars with banded spectra and sometimes bright lines (in the case of Long Period

* In his "System of the World" (1727), Newton showed, assuming that the planet Saturn reflects a quarter of the sunlight on it, that the Sun, if removed to a distance from which it would shine as a star of Saturn's stellar brightness (about $1^{m}.0$ with the rings edgewise), would have a disc a very small fraction of a second in diameter. (It would be $0''.0056$).

variables). There is also a relatively small number of stars of R, N and S types (see Appendix B).

The existence of a great diversity in luminosity and size among the stars has long been obvious from the composition of star clusters. There was, however, no knowledge of any systematic trend until in 1905 Professor Hertzsprung pointed out that the absolute magnitudes of the redder stars, derived from trigonometrical parallaxes and proper motions, were divisible into two distinct classes, one of great luminosity and the other relatively faint. As these stars are of similar colour and spectra and presumably therefore of about the same surface brightness per unit of area, they must be of very different sizes to account for the great inequality in the luminosities of the two classes. The names "giant" and "dwarf" were therefore adopted to indicate this disparity in dimensions. In 1913, H. N. Russell independently reached the same conclusion as Hertzsprung. An extract from his summary of the facts follows :—

"The surface brightness of the stars diminishes rapidly with increasing redness. . . . . The mean density of the stars of classes B and A is a little greater than 1/10th that of the Sun. The densities of the dwarf stars increase with increasing redness from this value through that of the Sun to a limit which cannot at present be exactly defined. This increase in density, together with the diminution of surface brightness, accounts for the rapid fall in luminosity with increasing redness among the stars. The mean densities of the giant stars diminish rapidly with increasing redness from 1/10th that of the Sun for class A to less than 1/20,000th of the Sun for class M. This counteracts the change in surface brightness and explains the approximate equality in luminosity of all these stars."

This statement is founded on observational results, described more fully later, study of eclipsing binary systems, considerations of the relation between surface brightness and colour and also on the work of the physical scientist. In the laboratory the relations between temperature and radiating power have been determined for fairly high temperatures and the distribution of energy in the different wave lengths has been ascertained. These have given laws of radiation which are exact when applied to a perfect radiator or "black body." Material which is blackest when cold, shines brightest and radiates most heat when it is hot, *i.e.*, its emitting power is large if its absorbing power is great. The perfect radiator would appear absolutely black when cold; its radiative properties are the simplest possible and can be derived theoretically and experimentally. The distribution of radiative energy in the spectrum of most stars is found to be similar to, or not very dissimilar from, that of this theoretical black body and consequently the effective temperatures of the stars can be fairly closely estimated. (See Appendix G). The approximate amount of light radiated per unit of surface may then be computed, and if we know the star's distance and the amount of light received from it, the diameter can be calculated. Sizes calculated in this way are found to agree with the giant and dwarf grouping, giving great difference between M giants and dwarfs and progressively less disparity with increasing temperature through K, G, F, to A and B type.

Another and more direct method of enquiry has been developed by means of an application of the principle of light interference. An "interferometer" at Mt. Wilson Observatory has enabled astronomers to measure the apparent angular diameters of certain giant stars as given in the table, Sirius and the Sun being added for comparison. The diameters in miles are derived from the angular diameter and the parallax by the formula :—

$$\text{Diameter in miles} = \frac{\text{Angular diameter}}{\text{Parallax}} \times 93{,}000{,}000$$

Table I

Star.		*Spectrum.*	*Angular Diameter.* ″	*Parallax.* ″	*Diameter in miles.*
αHerculis	...	M5	0·030	0·004	700,000,000
Betelgeuse	...	M2	0·047*	0·012	363,000,000*
Mira Ceti	...	M5*ev*	0·056*	0·017	307,000,000*
Antares	...	*c*M0	0·040*	0·015	248,000,000*
α Ceti	...	M0	0·012	0·011	97,000,000
β Pegasi	...	M5	0·021	0·020	97,000,000
β Andromedae		M0	0·016	0·033	45,000,000
Aldebaran	...	K5	0·020	0·059	31,000,000
Arcturus	...	K0	0·020	0·092	20,000,000
Sirius	...	A0	0·0065	0·376	1,600,000
Sun	...	G0	—	—	864,000

* Maximum value : variable diameter.

The first nine of these stars are giants, the two last are main sequence stars. The difference in diameters is a striking confirmation of the giant and dwarf grouping, although it must be appreciated that the diameters in the first half of the table are not close values owing to the uncertainty of parallaxes of such small amount.

Studies of the grouping of the stars by spectral types and absolute magnitudes were at first largely dependent on directly measured trigonometrical parallaxes, or on distances derived from

proper motions. More recently, however, the quantity of data has been much enlarged by modern methods of estimation of distances (see Appendix D). Fig. 1 shows the results for more than 2000 stars, as plotted by H. D. Curtis.

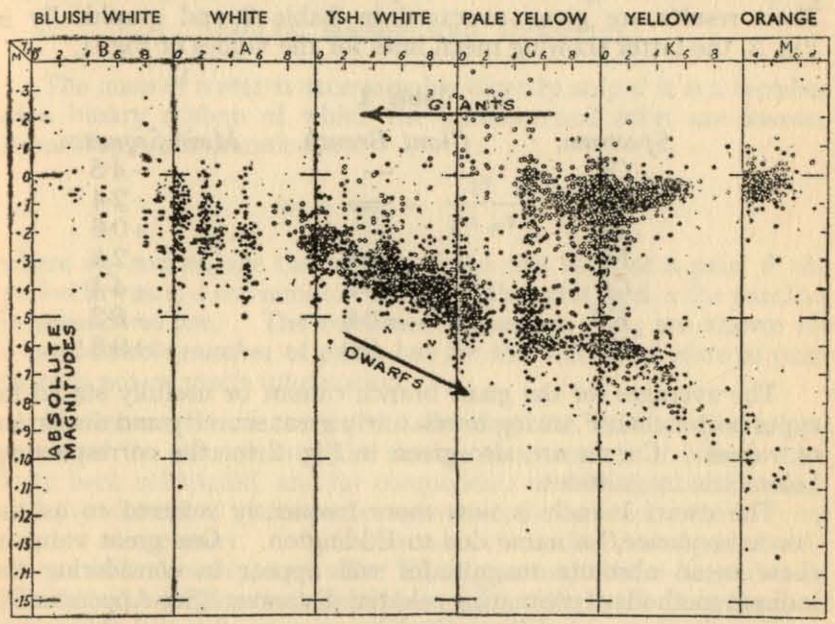


FIG. 1—THE GROUPING OF STARS INTO GIANTS AND DWARFS (after CURTIS),

showing the results of measurements of 2375 stellar distances and brightnesses. The stars are all plotted for the magnitudes at which each star would shine if placed at a distance corresponding to a light journey of thirty-two and a half years (parallax one tenth of a second of arc), so that their true relative brightnesses are as shown. The grouping into two branches, one of very bright stars averaging nearly one hundred times the Sun's luminosity and the other branch of stars diminishing in light with increasing redness of colour, is well brought out. In the diagram the dots and circles indicate the methods by which the parallaxes (on which the absolute magnitudes are based) were determined

. = modern direct (photographic only). o = spectroscopic only.
. = direct and spectroscopic or dynamical. ₒ = dynamical only.

Most of the naked-eye stars are giants, the proportion of dwarfs increasing generally as the limit of apparent brightness is reduced.

It will be noted in Fig. 1 that the difference in average luminosities of the two classes of stars, giant and dwarf, varies from nearly ten magnitudes (a ratio of 10,000 to 1 in light output) in the case of M stars, through about four magnitudes (a ratio of 40 to 1) in G type, to zero in the hotter stars.

Mean Absolute Magnitudes.

The relationship between absolute magnitude and spectral type has been the subject of much research by astronomers who have published mean figures based on parallaxes found by all methods. Their results are given averaged in Table 2 and graphically in Fig. 2, the latter showing mean lines for the values of Fig. 1.

Table 2

Spectrum.	*Giant Branch.*	*Main Sequence.*
O5	—	−4·5
B0	—	−2·4
A0	—	+0·6
F0	−0·6	+2·6
G0	+0·3	+4·4
K0	+0·6	+6·2
M	0·0	+9·8

The averages for the giant branch cannot be usefully stated for types hotter than F, owing to relatively great scarcity and dispersion of values. Curves are also given in Fig. 2 for the corresponding bolometric magnitudes.

The dwarf branch is now more frequently referred to as the "main sequence," a name due to Eddington. One great value of these mean absolute magnitudes will appear in considering the indirect methods of estimating celestial distances. (See Appendix D).

Certain stars are characterised by very narrow and sharp lines in the spectrum; these stars are denoted by the use of the letter *c*.

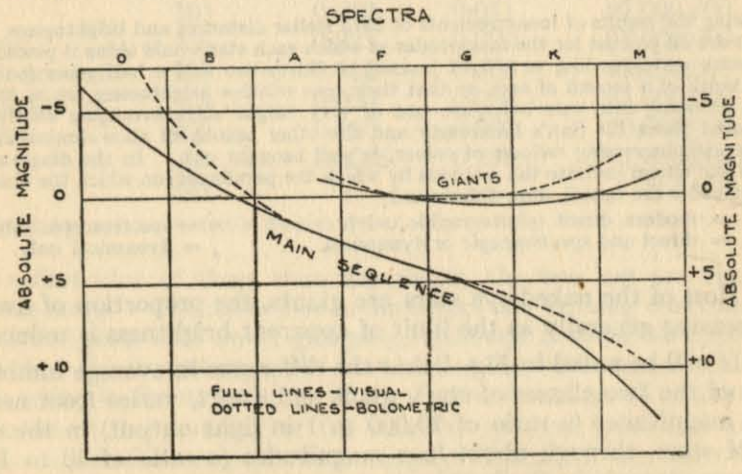


Fig.. 2. — Mean Absolute Magnitudes

Typical examples are ϵ Canis Majoris (*c* B1), αPersei (*c* F5) and α Scorpii (*c* M0); such stars are known to be luminous super giants. The prefixes *g* and *d* are used to denote giant and dwarf stars respectively; as, for example, Arcturus, *g* K0, and Procyon, *d* F5.

Stellar Masses and Densities.

The mass of a star is ascertainable directly only if it is a member of a binary system of which the parallax and orbit are known. From Kepler's harmonic law,

$$m_1 + m_2 = \frac{a^3}{P^2 \pi^3}$$

where m_1 and m_2 are the masses of the two stars of a pair, P the period in years, a the semi-axis major of the orbit, and π the parallax in seconds of arc. The combined masses $m_1 + m_2$ are known for a considerable number of pairs, but for the individual stars of pairs there is not so much information.

By means of measurements showing the mutual perturbing action of the components, the masses of a number of binary stars have been calculated, and for components of eclipsing binary pairs, and (by statistical methods) for spectroscopic binaries, with varying degrees of accuracy. This showed a marked correlation between mass and luminosity, and when Eddington and others derived from theoretical considerations formulae giving bolometric magnitude as a function primarily of mass and secondarily of temperature, corresponding fairly closely to observed results, a very great step forward in astrophysics was achieved.

Simpler empirical formulae have been published which connect luminosity with mass, one of which, derived by the writer, of some value for quick estimation of approximate masses or luminosities, is as follows :—

$$\text{Log Mass (Sun} = 1) = K\left(2^{\frac{10-M}{5}} - 2{\cdot}05\right)$$

K being 0·31 when M is visual absolute magnitude, and 0·26 when bolometric values are employed, the use of the formula in the latter form being preferable.

There is a class of stars which do not conform to this mass-luminosity relationship. These are the "white dwarfs," about 80 of which are listed. The best known are the companion of Sirius and the B component of o^2 Eridani. When distance and mass are known (the latter for such as are components of a binary), diameters can be estimated, using the surface brightness appropriate to the spectral type, which is usually that for stars whiter and hotter than the Sun ; the densities are then computed and values of the enormous order of 50,000 times that of the Sun are found.

In the case of Sirius B (mass 0·96 of the Sun's) the absolute bolometric magnitude for its mass would normally be of the order of +5, but it is found to be +11·3 or about 300 times fainter than the normal. The spectrum is between A5 and F0 and the diameter, calculated as in Appendix E, is only about 24,000 miles, giving a mean density 45,000 times the Sun's or about one ton per cubic inch. These extraordinary figures were confirmed by Adams at Mt. Wilson Observatory and later by Moore at Lick Observatory. According to the general theory of relativity a large mass acts on light emitted from it so as to increase its wave length. This effect is not great enough to be observed in an ordinary star, but in one of large mass and relatively small diameter it should be possible to measure it. For Sirius B the displacement should be that corresponding to a velocity of 12 miles per second and exactly that amount was found by Adams and by Moore.

The white dwarf companion of o^2 Eridani mentioned above is of about the same luminosity as Sirius B (absolute magnitudes +11·1 and +11·3 respectively). Its spectrum is of a hotter type, A0, and the diameter corresponding is 16,700 miles, which with a mass of 0·455 of the Sun, gives a mean density still higher—63,000 times the Sun's. Even greater densities seem probable for certain other white dwarfs, the masses of which have been estimated on the assumption that part of their radial velocities is a "relativity shift."

White dwarfs must be quite frequent, particularly as they are not easy to find and identify owing to their low luminosity. In fact, Luyten considers that perhaps one in twenty or thirty stars will prove to have white dwarf characteristics, which would make the class one of the commonest in space.

A number of stars of an abnormal sub-dwarf kind have recently been noted. With spectra similar to those of white dwarfs (A and F), their absolute magnitudes fall between the main sequence and the white dwarfs on a Russell-Hertsprung diagram (as Fig. 1). Their diameters are of an order of a third or a half that of the Sun or about ten times that for white dwarfs, but their densities, although certainly abnormal, are much less.

At this stage it will be of interest to present in tabular form figures which give a rough idea of mean figures for absolute magnitudes, mass, diameter and density for the commonest star of each type, based on the observational data and empirical mass-luminosity relationship of the preceding pages. Table 3 gives these particulars for giants and main sequence. The absolute magnitudes are as in

Table 2 and Fig. 2 ; mass is estimated by means of the empirical formula, using bolometric magnitude ; diameter is calculated from the formula—

$$\log \text{diameter (Sun} = 1) = 0{\cdot}2\ (J + 4{\cdot}9 - M)$$

(See Appendix E).

For mass, diameter and density (mass/diameter³) the units are the values for the Sun.

Table 3

ABSOLUTE MAGNITUDES, MASSES, DIAMETERS AND DENSITIES OF STARS OF VARIOUS SPECTRAL TYPES.

GIANTS.

Spect.	$M_{vis.}$	$M_{bol.}$	Mass.	Diam.	Density.
B0	—	—	—	—	—
A0	—	—	—	—	—
F0	−0·6	−0·7	3·9	7·9	0·008
G0	+0·3	+0·2	3·0	9·5	0·0035
K0	+0·6	+0·0	3·2	21	0·00035
M0	0·0	−1·5	5·6	75	0·000013

MAIN SEQUENCE.

Spect.	$M_{vis.}$	$M_{bol.}$	Mass.	Diam.	Density.
B0	−2·4	−4·6	27·5	6·6	0·10
A0	+0·6	+0·3	2·9	2·5	0·19
F0	+2·6	+2·5	1·6	1·8	0·27
G0	+4·4	+4·4	1·1	1·3	0·50
K0	+6·2	+5·9	0·85	0·95	0·99
M0	+9·8	+8·4	0·6	0·6	2·8

Researches on the O-type stars indicate a mean visual absolute magnitude of about −4·0, and masses of about 30 to 50 times the Sun's. But it may be noted that the relativity effect mentioned earlier appears to have been observed in certain O stars of high luminosity and mass in galactic clusters, and from their probable surface temperatures, luminosities, and observed shifts of spectral lines to the red as compared with the fainter and less massive stars of the clusters, Trumpler has derived diameters of 7 to 20 times and masses of 75 to 300 times the Sun's. Mean densities of the order of 0·04 to 0·25 of the Sun's seem likely. The N and R types appear to be of considerable luminosity and mass, averaging about −2 and −0·5 absolute magnitudes respectively while the S stars are of the order of −1·5.

REFERENCES—Part I—Chapter I

Author.	*Publication.*	*Subject.*
Rev. John Michell,	*Phil. Trans. Royal Socy.*, 1767 and 1784.	Hypothetical dimensions and distances of stars.
H. N. Russell,	*Popular Astronomy*, **22,** 19.	Giant and dwarf theory.
H. C. Wilson,	*Popular Astronomy*, **29,** 189.	Interferometer description.
W. H. Adams,	*Proceedings of the American Academy of Science* **11,** 382.	Companion of Sirius.
A. S. Eddington,	"The Internal Constitution of the Stars."	General.
L. Goldberg and L. H. Aller.	"Atoms, Stars and Nebulae."	General.

Chapter II

THE MOVEMENTS, NUMBERS AND DISTRIBUTION OF THE STARS.

Stellar Movements

THESE may be divided into two observational categories, apparent angular motions (proper motions) and velocities in the line of sight spectroscopically measured (radial velocities) of both of which many thousands are now known. The motion of a star may be in any direction in space, but only that component at right angles to the line of sight will be the cause of apparent displacement in the sky relative to other stars. Proper motion is compounded of the angular displacements caused by the star's own movement and by the movement of the solar system in space. Large proper motion usually means proximity rather than great space velocity; on the average the brightest stars, being nearer than the fainter ones, have larger proper motions. Nevertheless, when individual stars are considered, it is found that the biggest motions belong to rather faint stars, as will be seen from the following short list to which some similar examples discovered lately could be added.

Table 4

Star.	*Mag.*	*Annual proper motion.* ″
Munich 15040	9·7	10·3
Cordoba V^h 243	9·2	8·8
Groombridge 1830	6·4	7·0
Lacaille 9352	7·4	6·9
Cordoba 32416	8·3	6·1
61 Cygni	5·4	5·2
Wolf 359	13	4·8
Lalande 21185	7·6	4·8
ε Indi	4·7	4·7
Lalande 21258	8·6	4·5
o^2 Eridani	4·5	4·1
Wolf 489	13	3·9
μCassiopeiae	5·3	3·8
α Centauri	0·0	3·7
Washington 5583-4	8·5	3·7
Cordoba 29191	6·7	3·5
e Eridani	4·3	3·2

In more than 200,000 measured annual proper motions, the following are found :—

2″ or more,	at least	50 stars.
1″ ,, ,,	,, ,,	200 ,,
0·5″ ,, ,,	,, ,,	2400 ,,

One proper motion worthy of special reference is that of Arcturus (magnitude 0·2). From its movement of about a degree of arc and that of Sirius of half that amount, since the time of Ptolemy, Halley, in 1718, discovered the proper motions of the stars.* Arcturus moved at the rate of 2″·3 per annum or 115 times its own diameter of 0″·02 as found by the interferometer. This movement is due to a relatively great velocity, at right angles to the line of sight, of 74 miles per second, as its distance is about 35 light years from us. The annual proper of Sirius is 1″·3.

The Sun's Motion in Space

The motion of translation of the Solar system with reference to the stars in its neighbourhood (*i.e.*, within about 1000 light years), first discovered in 1783 from the directions of proper motions of only 13 stars by Sir W. Herschel, shows itself by an apparent recession of the stars from a point in Hercules, and a closing up of the stars towards the part of the sky diametrically opposite, the co-ordinates of these two points, the Solar Apex and Antapex, being R.A.18^h Dec. 30° North, and R.A. 6^h Dec. 30° South, respectively. The line of sight velocities of the stars also show clearly the same direction of motion of the Sun, most of the stars in the hemisphere towards which the motion is directed having radial velocities of approach (*i.e.*, negative values), while in the other half of the sky they are recessive (positive values). This is well shown in the illustration, Plate 1.

By means of stellar radial velocities the rate of motion of the solar system with reference to the surrounding stars can be best found, and this may be taken as about 12·5 miles per second. Investigations have shown, however, that both the direction and velocity of the solar motion seem to depend on the magnitudes of the stars to which they are referred and also to some extent on their spectral type. The velocity appears to be greater when faint stars are employed, being considerably greater than the figure given above when only dwarf stars are employed in the calculation.

* The tremendous increase in accuracy of measurement of stellar positions, on which proper motions depend, since the earliest times, is shown by the following estimates of average errors : Hipparchus (2nd cent. B.C.),4′ ; Tycho Brahe (16th cent.), 1′ ; Flamsteed (17th cent.), 10″ ; Bradley (18th cent.), 2″ ; Bessel (heliometer, early 19th cent.), 0″·2 ; first photographs (mid-19th cent.), 0″·1 ; modern long-focus photographs, 0″·025. Before Flamsteed's time telescopes were not used.

Proper Motions, Radial Velocities and Spectral Class.

The table gives averages for the brighter stars ; the radial velocities are corrected for the effect of the Sun's motion.

Table 5

Spectral Class.	*Mean Annual Proper Motion. Seconds of arc.*	*Spectral Class.*	*Mean Radial Velocity miles per second.*
O and B	0·028	B0-B5	4·6
A	0·05	B8-A3	5·0
F	0·079	A5-F2	7·7
G	0·052	F5-G0	9·8
K	0·057	G5-K2	9·6
M	0·050	K5-M3	10·3

There is a rough general correspondence in these proper motions and radial velocities. The O and B stars are highly luminous ; and on the average at great distances, their proper motions being thus very small. The increase in radial velocities with advance in spectral class is marked by a progressive reduction in mass, the more massive stars moving more slowly.

The K-Term in Radial Velocities

Professor W. W. Campbell, of Lick Observatory, found in his radial velocity determinations that there appeared to be a systematic recessive motion of the stars from the Sun, shown by an excess of positive over negative values, which is greatest in the case of the B type. This apparent movement of expansion seems *a priori* very unlikely, and has led to explanations being offered other than movement of the stars in space, such as downward convection currents in stellar atmospheres, a relativity effect greater in stars of large mass or high density shifting the spectral lines towards the red, and systematic errors in the wave lengths of the spectral lines employed. The amount of the K-term in B stars is about 3·5 miles per second recessive, and the probabilities seem to be that it arises from a complex cause in which are to be found downward currents in the stellar atmospheres (which appear to be greatest in hot stars like B type), relativity shift (also great in the B type stars which are massive and relatively small in diameter as compared with cooler giants), with perhaps systematic space motion and some effect of erroneous wave lengths of the spectral lines. The opinion is held generally, however, that this K-effect requires careful further study both observationally and analytically.

Kinetic Energies of Stellar Motion

When the space velocities of stars are derived from radial velocities and motions at right angles to the line of sight, corrected for the Sun's movement in relation to neighbouring stars, kinetic energies of motions, (mass × $\left(\frac{\text{velocity}}{2}\right)^2$), can be computed, using mean masses appropriate to the spectra or luminosities of the stars concerned. Some investigators have found that these energies appear to be fairly constant for several of the different spectral types. There are notable exceptions, however. The B type have smaller values than usual, while for K and M giants they are somewhat greater and for short period Cepheids they are much larger. Uniformity of kinetic energy would indicate equipartition of energy among the stars, but it is perhaps too much to expect equipartition of energy in a mixture probably composed of interpenetrating systems, which in themselves might show more approach to equipartition if the necessary segregation of stars could be made for an investigation. Only in a system composed of stars which have been neighbours practically from their origin, does it seem reasonable to expect equality of kinetic energy between the more massive and less massive stars, the former moving more slowly. A mixture of systems might easily conceal any such tendency, especially if the mean masses of the stars in the systems were not similar in amount.

On the other hand, these individual space velocities, relative to the neighbouring stars as a frame of reference, are probably only the more or less random differences among stellar orbital motions round the centre of the Galaxy, which will be referred to in a later section of this chapter.

Parallaxes from Proper Motions

As already stated, part of a star's angular proper motion is due to the solar motion in space, and in order to ascertain the motions of the stars at right angles to the line of sight, it is necessary to separate the component which is caused by the Sun's movement. This component is called the "parallactic motion," and is usually referred to as the υ-component. It is that component which is on the great circle passing through the solar apex and the star. The other component, at right angles to this, is the τ-component. Each gives a method of finding the average distance of a group or class of stars or other objects. Using the parallactic motion, the individual random motions are assumed to cancel, and the average parallax results as follows :—

$$\text{Mean parallax} = 2{\cdot}94 \; \frac{\overline{\upsilon \sin \lambda}}{V_0 \, \overline{\sin^2 \lambda}}$$

V_0 being the solar velocity, λ the angle between the solar apex and the star, and υ the parallactic component of the annual proper motion in seconds of arc. The bar over the quantities indicates that averages for the group of stars are to be employed.

In the case of the τ-component,

$$\text{Mean parallax} = 2{\cdot}94 \; \frac{\overline{\tau}}{\overline{V}}$$

V being the mean of the radial velocities, corrected for the solar motion, in miles per second, of the stars concerned. In both formulae 2·94 is the velocity in miles per second corresponding to a motion per annum of one astronomical unit (mean distance from earth to Sun).

Should the mean corrected radial velocity be less than about eight miles per second, the υ-component method gives the better results, but for stars of greater velocity the use of the τ-component is to be preferred.

From studies of proper motion, Seares finds that the solar motion varies with the magnitudes of the stars employed in the calculation, so that

$$\text{Solar velocity in miles per second} = 8{\cdot}0 + 0{\cdot}75\, m,$$

where m is apparent visual magnitude. Seares's latest values of mean parallax for stars of visual magnitudes down to the 13th, are given in Table 6. The second column is according to the above formula, the third is for a constant solar velocity of 12·5 miles per second.*

Table 6

Mean Parallaxes of Stars of given Magnitudes

Mag.	*Using formula. Seconds of arc.*	*Using 12·5 miles per second.* ″
1	0·0830	0·0580
3	0·0376	0·0307
5	0·0175	0·0164
7	0·0082	0·0087
9	0·0039	0·0045
11	0·0018	0·0024
13	0·0009	0·0013

* The figures are averages for the whole sky. For Milky Way regions they are about an eighth smaller ; near the Galactic poles a third greater. These differences are due to the greater proportion of stars of lower absolute magnitudes found among stars of a given apparent magnitude as Galactic latitude increases.

It will be appreciated that these figures can only be taken as averages, since the stars of a particular magnitude in any star field are of very different luminosities and therefore range over a considerable distance. But they may be useful for a number of stars in an area, and, for instance, in correction of relative trigonometrical parallaxes to absolute values by their application to the comparison stars used. And they are also of value when counts of numbers of stars to different apparent magnitudes are being utilised to obtain some idea of distances for involved objects such as nebulae or obscuring clouds. (See page 111).

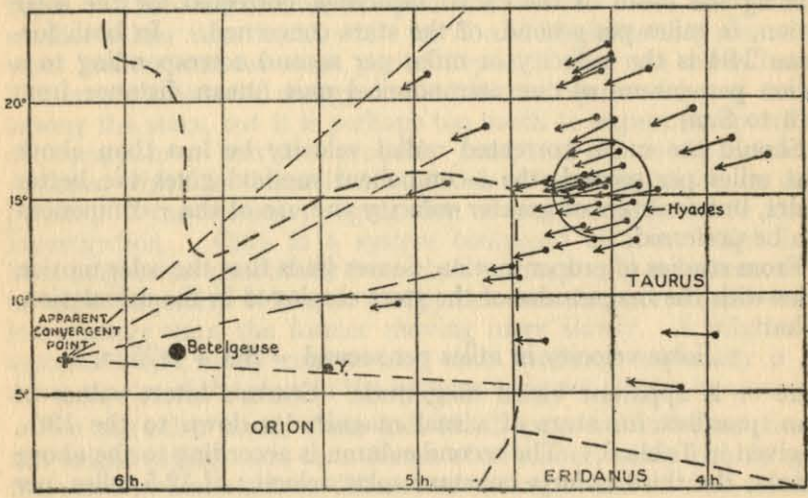


FIG. 3—TAURUS MOVING CLUSTER

More than forty stars are known to have apparent converging movements towards a point not far from the bright red star Betelgeuse. By these movements and the velocity in the line of sight measured by the spectroscope, the distance of the group has been found to be such that light takes 130 years to travel from these stars to us.

(The lengths of the arrows correspond to motion in about 65,000 years).

The Moving Clusters

It has been known for a long time that there is community of motion amongst certain stars for which physical connection would not otherwise be clear. In 1869, Proctor pointed out that five stars in the Plough had parallel proper motions and he also drew attention to the same features for certain stars in the Hyades. Later, work by Boss, Eddington, Kapteyn, Rasmuson and others indicated the probability of connection in these and a number of other groups. The chief are the Taurus (Hyades) cluster, the Ursa Major group,

the Perseus cluster, the Scorpio-Centaurus group, the Stars in Coma Berenices, a group of which 61 Cygni seems to be a member, and the stars in Orion.

In the Taurus group there are nearly 80 stars, ranging from about 3·5 to 6·0 magnitude and spectra A to K, the proper motions of which strikingly converge to a point in the sky about 6° east of Betelgeuse (see Fig. 3). The receding radial velocities of a number of these stars being measured spectroscopically, the true paths can be computed, assuming that they are really parallel in space, by a simple trigonometrical calculation; the convergence being thus assumed only apparent and due to the recessive movement from us. The parallax can also then be derived as about 0″.025, a value confirmed by several other methods. The diameter of this cluster is about 50 light years, or roughly 40 per cent of its distance from us.

The Ursa Major group is a very large and scattered one, discovered by Hertzsprung, who found that it contained stars in all parts of the sky, including such prominent members as Sirius, β Aurigae, β Eridani and α Coronae Borealis, as well as the five stars, β, γ, δ, ϵ and ζ Ursae Majoris. More than 40 stars are believed to belong to it, and it has a flat disc shape disposed perpendicularly to the galactic plane, 130 light years in its largest diameter, and moving as a whole parallel to the Galaxy.

The Perseus group, discovered by Kapteyn, Boss and Eddington almost simultaneously, has at least 45 stars in it, from second magnitude to below sixth, nearly all of B type. Most of the stars in this group lie in an extended chain formation in the sky, which may indicate a flat disc shape as in the Ursa Major group. In this cluster the motion, according to Rasmuson, is also parallel to the Galactic plane and the distance is roughly 330 light years.

The Scorpio-Centaurus group contains more than 150 members, mostly of B type, scattered over the sky in a zone about 50° wide, from 8^h to 18^h R.A., the width of the zone increasing somewhat in the direction of Right Ascension. Such prominent stars as α and β Crucis, β and η Centauri, β Scorpii and possibly Antares seems to be members, the average distances varying from about 160 to 250 light years, the narrow end of the zone apparently containing the nearer objects. Some of the stars in the Southern Cross and its vicinity belong to this group and are at a distance of about 230 light years. The motion of the cluster is also nearly parallel to the Milky Way plane and is in the direction of its own longest axis.

The Coma Berenices group contains at least 75 stars from about 4·5 down to 9·0 or fainter, situated between 11^h and 15^h R.A. and Dec. 10° to 50° North, all moving nearly westward in the sky.

The distance to the centre of the cluster is roughtly 240 light years. The 61 Cygni group is composed of about 60 stars scattered all over the sky from about the third to the eighth magnitudes. It is marked by three sub-groups of F, G and K type stars. The physical connection of the stars in Orion is considered to be shown by their similar radial velocities, on an average about 13 miles per second recessive. As their situation is roughly directly opposite to the direction of the solar motion towards Hercules at about the same speed, this shows only the reflex effect of that motion. The distance of the group (much nearer than the great Orion nebula) is about 600 light years.

The exact status of some of these extended moving clusters has recently been shown to be very doubtful. A few of them are certainly connected groups moving together with reference to the surrounding "field" stars. Although those of Taurus, and Ursa Major are undoubtedly real, there appears to be not the same certainty for the groups of Scorpio-Centaurus, Perseus and Orion, which are perhaps composed only of field stars with small individual motions.

Rotation of the Galaxy

As might be anticipated, the flattened form of our Galactic system suggested by the Milky Way zone, has in the past led to conjectures that it is in rotation in its own plane. The motion of the Sun with reference to its surrounding stars discovered by Herschel, was surmised (erroneously) by some to be an orbital movement round the centre of the Galaxy. Following the analogy of the planets revolving round the Sun, several have speculated on the possibility of the existence of a central sun of enormous mass. Kant thought that this might be Sirius, while Herschel put forward the idea that the great globular cluster in Hercules (M 13) or, alternatively, the "compressed parts of the Milky Way," might be the governing mass. Madler believed, however, that the ruling power is not concentrated in any single mass, but that it is situated at the centre of gravity of the whole system of the stars. From certain indications of stellar proper motions he conjectured that this point is in the vicinity of the Pleiades cluster. These speculations were all (except Herschel's alternative) ruled out ; in the case of Sirius by inadequacy of mass, and for the Hercules cluster and the Pleiades, by positions much too far out of the Galactic plane in which the rotation might be supposed to occur. If there is rotation and the control is principally by a concentration of mass at the centre, the speeds of the stellar motions round the centre will decrease with distance from it, just as in the Solar system, with the mass concentrated in the Sun, we find the orbital motions of the planets to be slower for those farthest from it. In the case of a system of stars of more or less uniform distribution, the greatest attraction is found at the outside parts, as there the mass of all the stars is acting in the one general direction. As we pass inwards the attraction towards the centre is acted against by outward attractions and at the centre there is a balance of forces. In this case the bodies on the outskirts would move the most rapidly. Evidence for or against rotation may be sought in proper motions and also in the differences of velocities in the line of sight connecting the star and observer.

If the stellar system rotates as one body so that the stars, although moving among themselves, keep on the average the same relative positions to each other, there will be no possibility, except by reference to the "Invariable Plane" of the Solar system (see *B.A.A. Journal*, **39**, 167), of discovering rotation of the system by means of relative changes in their positions or differences in their radial velocities. To use a homely illustration, if a number of people were situated on the spokes of a large rotating wheel at various distances from its axis, none of them could see any alterations of apparent position among themselves which would indicate rotation. On the other hand, if the rotation were such that the speeds decreased outwards, as is found in the planets of the solar system, then by study of the apparent cross motions and line of sight movements, rotation might be deduced and measured.

Among the most remarkable of recent achievements in astronomy may be placed a demonstration by such methods of a Galactic rotation of this nature. Stellar proper motions, and line of sight velocities of O, B, N type stars, Cepheid variables, *c* stars, planetary nebulae and inter-stellar diffused matter, all objects with distances ranging out to 2000 light years and more, have been studied by Lindblad, Oort, Plaskett, Joy and others, and results of such great consistency obtained as to leave no doubt that our Galaxy is rotating in its plane, in a clockwise direction as seen from the northern side of that plane, with great velocity, the speeds of revolution of the stars decreasing from the centre outwards. This centre is in exactly the same direction and at about the same distance away from us in the constellation Sagittarius, as is suggested by the distribution of stars and other objects in the Galactic system, and also by the disposition in space of the globular clusters surrounding it.

The velocity of revolution for the stars in the Sun's neighbourhood is found to be about 150 or more miles per second with a period of rotation of about 200 million years, which would require a controlling mass of the order of two hundred thousand million times that of the Sun. Strong support is given to these conclusions by consideration of the line of sight velocities of globular clusters. The system formed by these objects is much less flattened than the denser parts of the Galaxy itself and is presumably rotating more slowly if at all. The rotational general motion round the Galactic centre of the system of stars can therefore be related to this globular cluster system as a frame of reference, and is then found to agree with that derived from the motions of the Galactic stars. In fact, it can be shown quite simply from the radial velocities of the globular clusters that this is probably the case. Of twenty-one velocities (18 of them are given in Shepley's "Star Clusters," page 199), eight are recessive from the Sun, twelve are approaching, and one is zero. Seven of the eight recessive values are for clusters with Galactic longitudes in the half of the Galactic circle between 155° and 335° longitude, and eleven of the approaching twelve are in the other half. Two of the three remaining are at longitudes relatively near the accepted centre of rotation and the third (the zero one) is almost exactly at it.

As this centre in Sagittarius (longitude 330°) is close to the chosen point of division for the two halves of the Galactic circle (335°) this disposition of the radial velocities, which has been obtained by simple inspection, is what might have been expected for the centre of the rotation, and its direction, as determined from stellar motions. Or, alternatively, it might almost have been predicted* from the radial motions of the globular clusters alone, that the Galaxy would be found to rotate about a point in its brightest region in Sagittarius, the direction of rotation being so that the part in our neighbourhood is at present moving towards a goal beyond that region of the sky in which α Cygni is situated.

Study of the velocities of stars with speeds greater than about 60 miles per second, by Oort and others, led to the discovery that these bodies appear to be streaming systematically in the direction of the constellation Argo (R.A. 8^h, Dec. 44°S), the opposite part of the sky, in the direction Aquila - Cygnus - Cassiopeia, being strictly avoided by them. The explanation of this is to be found in the rotation of the Galaxy; and in fact this preferential motion constitutes in itself a corroborating fact.

It appears that most of the stars near the Sun have orbits round the Galactic centre of an approximately circular shape. Some (*e.g.*, the high velocity stars mentioned above, and other fast-moving bodies such as the short-period Cepheids and Long Period variables) probably have long elliptical orbits, crossing the Sun's orbit at a large angle, on their way into, or out from, their "peri-galactic" position. They will appear, as a class, to be moving rapidly back-

* The prediction would scarcely have been any bolder than that of Herschel's first determination in 1783 of the motion of the Solar system (see page 16).

wards towards Argo, which is 90° in Galactic longitude from Sagittarius, as compared with the Sun whose path crosses their orbits in its track round the Galactic centre; those ahead of the Sun having in general approaching line-of-sight velocities and those behind receding speeds. They will thus seem to have high space velocities, the Sun's speed in its orbit being, as stated, 150 miles or more per second.

This provided a satisfactory explanation for the high-velocity stars, but for the generality of stars in the Sun's vicinity another remarkable phenomenon had been discovered by J. C. Kapteyn earlier in 1904. This consisted of a general systematic motion suggesting two streams of stars passing through each other, each stream moving on the whole in a certain direction, although individual stars have movements relative to one another; the Sun, for instance, having a motion towards Hercules with regard to the neighbouring stars of about a twelfth the rate of its velocity of Galactic rotation. The streaming motion discovered by Kapteyn can be shown to be a natural consequence for the stars with orbits round the Galactic centre that are not circular. These stars are moving in elliptical orbits which, in the Sun's neighbourhood, have an inward or outward trend as compared with the average of the more circular motions of the nearby stars. When these outward and inward differences are considered, a preference is shown by them for a direction towards or away from the centre. This is what was found by Kapteyn—a direction lying nearly in the plane of the Milky Way in a line joining Scutum and Orion. Between this and the line from the Sun to the Sagittarius centre there is an angle of only 15°, a deviation no doubt capable of explanation on the accepted theory when further knowledge of the stellar movements concerned has been obtained.

Numbers and Distribution of the Stars.

Important determinations of the numbers and disposition of the stars over the sky were made by Seares and van Rhijn. The value of such data has been recognised since the gauges of the Herschels made between about 1780 and 1838. This work was continued by others, notably Seeliger, Pickering, Chapman and Melotte, Kapteyn, and Seares and van Rhijn. Progress in stellar photography has led to extensions of the counts to larger sky areas and to lower limits of brightness, and also to improvements in the accuracy of the stellar magnitude scales. It is in the last-named factor that the chief difficulty in the way of accuracy has lain, the problem being one of photometry of a range of brightness covering over 20 stellar magnitudes and therefore involving the setting up of accurate standards over an interval ranging in intensity more than

100,000,000 to 1, which is about the same as the ratio between the width of the Atlantic in our latitudes and a couple of inches. The difficulties are particularly great when visual methods are employed, large errors then occurring, but the introduction of photography, using a scale of stellar magnitudes defined by a field of stars near the North Pole of the sky, the "Harvard North Polar Sequence," has produced much more dependable results than formerly.

Down to ninth or tenth magnitude the numbers of the stars in each magnitude grade are known, all such having been catalogued. For the fainter stars, the numbers have been obtained by counts in sample areas.

Table 7 is the result of such methods applied under the direction of Seares and van Rhijn. The figures are for the whole sky (41,253 square degrees) down to the twenty-first visual magnitude—the limit visually of a telescope about 250 inches in aperture—corrections from photographic to visual magnitude having been made.

Table 7

TOTAL NUMBERS OF STARS BRIGHTER THAN A GIVEN VISUAL MAGNITUDE.

Mag.	*Number.*	*Ratio.*	*Mag.*	*Number.*	*Ratio.*
0	3		11	865,000	
		3·7			2·6
1	11		12	2,280,000	
		3·6			2·5
2	40		13	5,700,000	
		3·6			2·4
3	144		14	13,600,000	
		3·5			2·3
4	510		15	32,000,000	
		3·2			2·2
5	1,620		16	71,000,000	
		3·0			2·1
6	4,860		17	150,000,000	
		2·9			2·0
7	14,300		18	299,000,000	
		2·9			1·9
8	41,300		19	560,000,000	
		2·8			1·8
9	117,000		20	990,000,000	
		2·8			1·7
10	330,000		21	1,690,000,000	
		2·6			

It will be noticed that the ratio between the numbers of stars down to successive magnitudes steadily becomes smaller with decrease in brightness. It was thought that if this continued, as indicated by the run of the numbers, there could not be many stars fainter than about the thirtieth magnitude and that the total number of stars in our stellar system would be roughly thirty or forty thousand millions, *i.e.*, about 20 per human inhabitant of our globe. Seares and van Rhijn also found that the total light of the stars is equivalent to 1092 first magnitude stars and that 98 per cent of this light is from the stars brighter than 21st magnitude.

THE AMOUNT OF STAR-OCCUPIED SKY.

In view of the enormous numbers in Table 7, it is surprising to note the very small part of sky surface occupied by the stars of our system. An idea of this may be obtained as follows. The aggregate light is, as stated above, equal to 1092 first magnitude stars. This is equal to one star of $-6{\cdot}6$ magnitude, and it is obvious that the total disc area of the stars will be between that of, say, one B star or one M star of this visual magnitude, closer to the latter owing to the great preponderance of later spectral types. From the formula in Appendix E it can be found that the angular diameters of these hypothetical stars are $0''{\cdot}04$ and $1''{\cdot}0$ respectively. There will not be much wrong therefore in a statement, meant merely to indicate the smallness of the fraction of the sky, that an area substantially less than that of a disc a second of arc in diameter is occupied by the luminous stellar material of our Galaxy. That is to say, less than the area covered by a half-penny at a distance of over three miles.

LOSS OF LIGHT IN SPACE.

If the stars were equally distributed in space at all distances from us and if there were no loss of light in space, there would be a constant ratio between the numbers of stars brighter than successive magnitudes. The light ratio being 2·512 for one magnitude difference, the ratios of distances and spherical volumes corresponding are $2{\cdot}512^{\frac{1}{2}}$ (1·585) and $2{\cdot}512^{\frac{3}{2}}$ (3·98) respectively. The ratios of Table 7 being progressively less than this figure (3·98), there must be either a progressive thinning out of stellar light or a loss of light in space, or both. If there is a loss of light in its passage through space to us from the stars, then the density of stellar distribution does not necessarily decrease as we go outward from the Sun; which, moreover, need not occupy a central position in the space populated by the stars counted, as might otherwise be assumed.

It is now thoroughly established that there is interstellar absorption of light. The existence of dark Galactic nebulae near the central axis of the Milky Way has long been known. But what is perhaps more important in connection with the present discussion is the possibility of a more general presence of obscuring matter. Such a general obscuring medium has long been suspected* and has now been demonstrated to exist.

During the early years of the present century a number of investigations were made on the possible loss of light through reddening by interstellar material, without much in the way of a definite result. As regards general absorption an enquiry was made by Trumpler in 1930, using 100 Galactic or "open" clusters as his material. He assumed that clusters of the same physical type (see Table 22) would be of the same real diameter and the same total luminosity on the average.

According to these assumptions, clusters of a given angular diameter should have had the same apparent stellar luminosities, but he did not find this to be the case. The relative distance corresponding to apparent angular diameter came out less than the observed luminosities indicated, a general obscuration of 0·67 stellar magnitude per 3260 light years (1000 parsecs) being required to remove the discrepancy. Confirmation of a value of this order has been found by Joy, van Rhijn and others by different methods ; and Hubble's counts of the nebulae outside our Galactic system at varying angles above the plane of the Galaxy (Galactic latitudes) have pointed to the existence of a layer of absorbing material in the central plane, extending to a distance of at least 6000 light years from the Sun, about 3000 light years thick, which would cause an obscuration in a path perpendicular to the plane of about half a stellar magnitude (photographic). This layer adds its effect to that of the obscuring clouds where these are found. (See p. 109). Detailed study of the effects indicates, however, that the absorptive material is not uniformly distributed and that the reductions in apparent brightness caused by it vary somewhat in different directions in space.

* The following passage from Newton's "System of the World" (1727) is of interest : "Some may, perhaps, imagine that a great part of the light of the fixed stars is intercepted and lost in its passage through so vast spaces and upon that account pretend to place the fixed stars at nearer distances, but at this rate the remoter stars could be scarcely seen. Suppose, for example, that three-fourths of the light perish in its passage from the nearest fixed stars to us . . . . the fixed stars that are at a double distance will be 16 times more obscure, viz., 4 times more obscure on account of the diminished apparent diameter ; and, again, 4 times more on account of the lost light. And . . . . at a triple distance will be $9 \times 4 \times 4$, or 144 times more obscure . . . . at a quadruple distance $16 \times 4 \times 4 \times 4$, or 1024 times more obscure. . . . ." Newton evidently did not favour the idea. But the absorption he supposes in his example is very much greater than generally found.

Study of the colours of B stars and other objects bright enough for study at great distances, has shown that they appear redder than the normal of the same types nearer to us. The effect as expressed in stellar magnitudes (see later section, on colour indices), amounts to from about a fifth to as much as a half of the total general absorption. The absorbing clouds responsible for the reddening probably float within the general stratum of absorbing matter.

The great effect on estimates of distance which are based on apparent magnitudes of stars of known luminosities situated in the absorbing layer referred to, will be evident when it is stated that, with Trumpler's figure for the absorption, an apparent distance of 1000 light years has to be reduced by 8 per cent, one of 5000 light years by 29 per cent. and of 10,000 light years by 42 per cent. Even with a smaller absorption, which there is some reason to believe may be the case, of say $0^m{\cdot}5$ instead of $0^m{\cdot}67$ per 3260 light years, these percentages would be 6, 24 and 36 respectively. The effect becomes considerable therefore beyond, say, a thousand light years.

Interstellar Light Scattering and Absorption.

The obscuration by dust clouds referred to is caused chiefly by small particles, the total interstellar mass of which is relatively small. Ability to redden starlight entails sizes of particles smaller than about a thousandth of an inch in diameter ; others of larger dimensions simply obstruct the light without changing its colour, although the obstructed light is absorbed and later re-emitted as unobservable "heat" radiation. The deflection of light by the smaller particles is known as "scattering," and the bluer rays are those concerned, much as the light of the Sun is scattered by the earth's atmosphere, resulting in the blue sky and a yellowed or reddened Sun. Interstellar space also contains many atoms and molecules of gas which have little dimming effect, although their aggregate mass is larger than that of the bigger dust, or even greater sized, particles. This interstellar gas has been revealed by the spectroscope which has shown fine absorption lines caused by atoms of calcium, sodium and other elements such as potassium, titanium and iron, and recently some lines have been noted which are due to molecules of the hydro-carbon (C H), sodium hydride (Na H), and cyanogen (C N). The strongest of these lines were first found in the spectra of distant spectroscopic binaries, as "stationary lines," which did not change their position in the spectra, as did other lines because of orbital motion in the binaries. These distant stars were necessary for the discovery, a very great length of path through the gas being essential to produce sufficiently strong absorption lines to be visible. As a consequence of the great tenuity of the interstellar gas which produces them, the lines are fine and sharp, becoming stronger as the distance of the star is greater, and thus providing another useful measuring rod for estimating distances.

Within the last year or two it has been possible to discover, from the doubling (or even trebling or quadrupling) of the calcium lines, the existence of more than one intervening cloud each with a different radial velocity.* Another useful result from the measurement of velocities of interstellar gases is a definite confirmation of the rotation of the Galaxy, and its speed of revolution, as found from stellar radial velocities and proper motions. In all probability most of the elements found in the Sun and stars have atoms in some part of interstellar space, but usually so rarefied as to be undetectable, or of elements having spectral lines only in that part of the spectrum (the extreme ultra-violet) which is cut off from our study by the absorbing action of the earth's atmosphere. In fact, it has recently been found, by means of a specially-designed spectrograph, that *bright* lines of hydrogen and ionised oxygen are detectable in regions of the Milky Way ; the hydrogen lines are often apparently associated with O type stars, and no bright lines of the kind are evident in areas of the sky away from the Milky Way zone.

Concentration of Stars to Milky Way.

The crowding of stars towards the Milky Way zone has long been a familiar fact. This concentration in spite of any effect of obscuration in the lower Galactic latitudes, increases very much in the fainter stars, as will be seen from Table 8, which shows numbers of stars per square degree for different angular distances from the centre line of the Galaxy (Galactic latitude).

Table 8

Approximate Numbers of Stars per Square Degree at different Galactic Latitudes.

Down to visual mag.	*Whole sky.*	0°	20°	45°	90°
6·0	0·12	0·21	0·13	0·08	0·06
8·0	1·0	1·9	1·2	0·7	0·5
10·0	8·0	19	10·5	6·2	4·0
15·0	775	2100	870	350	160
20·0	25,000	80,000	22,500	4,200	1,750

* Oort considers that, on an average, the light from a star about 3000 light years away, will traverse five of these clouds on its way. There seems to be two classes of gaseous cloud, one of which has more of the molecules in its composition than the other ; in other words, broadly speaking, we may refer to molecular and atomic clouds of interstellar gas.

The increasing Galactic concentration in the fainter stars is brought out by the ratios between the numbers for 0° and 90°, which vary from 3·5 at $6^{m}\cdot0$ to 46 at $20^{m}\cdot0$. It is also strikingly illustrated by Seares's conclusion that 95 per cent. of the thirty or forty thousand million stars in our system are situated on the sky within 20° of the centre line of the Milky Way zone.

In the southern Galactic hemisphere the distribution is in general somewhat richer than for equivalent northern latitude. In Galactic longitude the stars down to eighteenth magnitude are concentrated about four times as highly in the direction of the Sagittarius region as in the opposite hemisphere of the sky. The brighter stars (down to about the ninth magnitude) are concentrated more towards Argo Navis than in the opposite parts of the sky.

As regards the relation of particular types of stars to the Galactic plane, the high luminosity O and B types are strongly concentrated ; and inside 15 degrees on either side of the centre line are to be found more than 90 per cent. of the Cepheid variable stars of period greater than one day. The Long Period variables show little or no concentration (see next chapter for a description of these variables).

Colour Index and Apparent Stellar Magnitudes.

It has long been known that mean colour index or photographic *minus* visual (or photovisual) magnitude ($m_p - m_v$), increases generally in the fainter stars. The reason for this has been variously explained ; for instance, as due to a greater proportion of late red dwarfs, or as caused by selective absorption of stellar light in space. Whatever be the explanation, the quantity is important for the purpose of transforming photographic magnitudes into visual magnitudes in the case of the fainter stars, for which only m_p is usually known. Seares gives the following formulae :—

Average colour index (whole sky) $= + 0{\cdot}50 + 0{\cdot}029\, m_v$
and ,, ,, ,, ,, $= - 0{\cdot}18 + 0{\cdot}071\, m_p$

The correction (for the whole sky) for transforming star counts for a grouping according to photographic magnitude into one according to visual magnitude, is $= - 0{\cdot}16 - 0{\cdot}050\, m_p$. For example, what is the visual magnitude corresponding for the whole sky to 17·0 photographic ?

$$\text{From the formula } m = 17{\cdot}0 - 0{\cdot}16 - (0{\cdot}050 \times 17{\cdot}0) = 16{\cdot}0$$

Colour index for a given magnitude is greater on the average with increase in Galactic latitude, the stars being therefore generally bluer in Milky Way regions ; this is owing to the greater concentration of the hotter B and A type stars there. Results by Kreiken show that the average colour index for the whole sky is somewhat less than that given by Seares, but that in any case the values are about half a magnitude less for Milky Way regions. In higher latitudes and also in parts of the Milky Way where there is evidence of the existence of dark clouds, the colour indices are roughly of the size given by Seares's formula.

The Luminosity Law.

That stars vary very much in luminosity has been obvious ever since the recognition of co-existence in physically-connected clusters of stars of very different brightness. The most luminous star so far known seems to be the eclipsing binary S Doradus, situated in the large Magellanic Cloud, for which star we find an absolute magnitude of about −8 for each component. One of the faintest known stars is the 11th magnitude companion of α Centauri (Proxima Centauri), which is about + 15 absolute magnitude.* This range, 23 magnitudes, means a ratio of light output of 1600 millions to one, or from about 160,000 times to about one ten-thousandth of the Sun.

To ascertain the relative frequency of occurrence of stars of different luminosities (the "Luminosity Law") has been the object of many investigations by Kapteyn, van Rhijn, Seares, Luyten and subsequent astronomers.

The first estimates by Kapteyn and others gave numbers, down to about 12th or 13th absolute magnitude which later investigations have found to be considerably too small at the fainter end, and the most recent results indicate many additional faint dwarf stars. It is now thought that the greatest star frequency is at about the 12th or 13th absolute magnitude (visual), and the faintest stars are perhaps of the twentieth absolute magnitude or thereabouts, *i.e.*, of a millionth of the Sun's luminosity. The true range of stellar luminosities is perhaps therefore a hundred times that mentioned above. The table gives an approximate idea of the distribution of the stars as a function of spectral class and visual absolute magnitude according to recent research.

Part A of the table gives the relation of absolute magnitude to numbers ; the figures in brackets are extrapolations which take into account, without accuracy in detail, the great number of faint dwarf stars. Part B shows the distribution by spectral types.

* About the faintest star observed so far is a companion to the dwarf red star, BD + 4°4048, which is several magnitudes fainter than Proxima.

Table 9

Number of Stars per Million Cubic Light Years near the Sun.

A

Absolute Magnitude (Visual).	*Number.*	*Absolute Magnitude (Visual).*	*Number.*
0·0 and brighter	4	10·0	240
1·0	8	11·0	270
2·0	20	12·0	300
3·0	40	13·0	310
4·0	62	14·0	(290)
5·0	88	15·0	(260)
6·0	115	16·0	(200)
7·0	150	17·0	(140)
8·0	185	18·0	(60)
9·0	215	19·0 and fainter	(20)

B

Spectral Type.	*Number.*	*Mean Abs. Mag. (Visual)*	*Spectral Type.*	*Number.*	*Mean Abs. Mag. (Visual)*
B0 – B9	4·7	0·0	*g* G0 – *g* G9	0·4	+0·5
A0 – A9	34	+2·5	*g* K0 – *g* K5	7	+0·5
F0 – F9	68	+3·5	*g* M0	1	0·0
d G0 – *d* G9	128	+6·0	N	0·01	0·0
d K0 – *d* K6	484	+7·5	R	0·01	+0·5
d M0 +	2250	+14	S	0·0003	−1·5

The mean absolute magnitudes given allow for the increasingly greater main sequence frequency as spectral type becomes later. The total number of stars in Table 9 is 2977 or, say, one star per 300 cubic light years roughly.

Spectral Type and Apparent Stellar Magnitudes.

The *Henry Draper Catalogue of Stellar Spectra* contains particulars of the spectral classifications of somewhat more than 225,000 stars. It is practically complete down to about $8^{m}{\cdot}75$ for the southern sky and to $8^{m}{\cdot}25$ for the northern hemisphere, the difference being due to the clearer atmosphere at the observatory at Arequipa, Peru, as compared with Cambridge, Massachusetts. The catalogue can be taken as complete therefore for the whole sky at $8^{m}{\cdot}25$ (photographic), to which limit there are nearly 60,000 stars with the following percentage distribution :—

Table 10

Spectral Types of Stars brighter than $8^m{\cdot}25$ (Photographic),

	Type.		*Percentage of Total.*
B	(B0 – B9)	... ...	11
A	(A0 – A5)	... ...	22
F	(F0 – F8)	... ...	19
G	(G0 – G5)	... ...	13
K	(K0 – K5)	... ...	31
M	(Ma Mb Mc)	... ...	3
	O, R, N, S	... ...	1

The K, A and F stars are the most numerous, accounting for nearly three-quarters of the total. More than half of the apparently brighter stars are of types hotter than the Sun, but of naked eye stars it is found that those of class KO are the most frequent. Class B contains a large proportion of the brightest stars, but the percentage for it decreases very rapidly among the fainter stars. With regard to disposition in the sky, the B and A type are closely confined to the Galaxy, but there is no marked concentration for F and G types, although for K and M there is a slight tendency to greater frequency in low latitudes. In general, it may be said that the types of greatest space-velocity are, as perhaps might have been expected, found to be dispersed farther than others from the Milky Way zone. It may also be said that on the average the stars of greater luminosity and larger mass are concentrated towards the Galactic plane.

The greater concentration as a whole of the fainter stars of early type spectrum towards the Galactic zone, is brought out for the tenth to eleventh magnitude stars of two Milky Way regions centred at about 40° and 160° longitude, using Harvard Observatory material in diagrams published by Shapley. These show about 44 and 56 per cent. respectively for stars hotter and for those cooler than F0 type in the first of these regions, and 35 and 65 per cent. for the other, in spite of the reduction in percentages of B types generally among the fainter stars as mentioned above.

Spectral Types and Distances

Using the material of the *Draper Catalogue*, average absolute magnitudes such as are given in Table 2, and counts of the number of stars found on 2300 square degrees of sky in fields at all longitudes along the central line of the Milky Way, Shapley has found the limiting distances and numbers of stars given below.

Table 11

Spectral Type.	*Surface number per square degree.*	*Distance limit in light years.*	*No. per million cubic light years.*
B0 – B5	29·7	2860	0·13
B8 – A3	96·9	1100	7·2
d A5 – *d* F2	18·7	455	19·6
d F5 – *d* G0	26·0	230	220
g G5 – *g* K2	69·0	1140	4·3
g K5 – *g* Mc	17·5	1400	0·6

The table does not take into account such relatively infrequent stars as Cepheid variables, or abnormally faint A stars, and is not continued to dwarf K and M type stars, which are much more numerous even than the dwarf F5 - G0 stars. Shapley concludes that for every B0 - B5 star there are about five giant M stars and seventeen hundred dwarfs like our Sun.

It is of interest to note that the aggregate luminosity and mass of the stars in Table 9 can be roughly computed to be equal to those of 1300 and 1400 Suns respectively. This indicates that the average unit of stellar mass in the million cubic years round the Sun radiates light at much the same rate as the same unit of solar mass. This is noteworthy in view of the great disparity in rates of radiation per unit of mass between a highly luminous star and a dwarf (see page 78).

Distribution in Galactic Longitude.

Attention has often been drawn to the high degree of concentration towards the Galactic plane of particular types of stars, and occasionally references are made to the nature of the distribution of various objects along the approximate great circle of the sky marked out by the Milky Way. A detailed investigation of this distribution is much to be desired and although what follows can hardly be taken to be such in any adequate sense it is put forward as a compilation of data which may be of some value.

In Table 12 ten classes of object are shown in percentages according to their distribution in quadrants of the Galactic circle, the zero of longitude being situated at R.A. $18^h\ 40^m$ where the circle crossed the celestial equator, the values of longitude increasing towards the east. The region of the Milky Way in each quadrant is indicated by the names of the constellations, although, of course, many of the objects are in other constellations of higher north or south latitude.

Classes (*c*), (*d*), (*h*) and (*l*) are notably concentrated towards the Milky Way zone; particularly the novae, for which the mean latitude without regard to sign is only 9 degrees, with the fainter ones more numerous towards Sagittarius. This concentration is also a feature of the distribution of Cepheid variable stars with periods longer than about three days, which it is noteworthy have considerably smaller space velocities than those of shorter period. Concentration towards the Galaxy is also fairly well marked in the case of eclipsing binaries. Galactic novae are all the temporary stars other than those objects appearing in certain spiral nebulae.

The quadrant of greatest concentration is shown by the figure in heavy type; the interpretation of these concentrations will be discussed in a later chapter.

The progression in longitude of the most favoured quadrant suggests concentration of the nearer bright objects towards the centre of the supposed Local Cluster, and of the more distant towards the Galactic centre in Sagittarius. (See Part III, Chapter I).

Table 12

PERCENTAGE DISTRIBUTION IN GALACTIC LONGITUDE.

Class of Object.	*Number.*	*Longitude* 90°-180° *Perseus to Orion.*	*Longitude* 180°-270° *Monoceros to Argo.*	*Longitude* 270°-360° *Centaurus to Sagittarius.*	*Longitude* 0°-90° *Aquila to Cassiopeia.*
(*a*) B8 - A3 stars brighter than $6^m.5$,	2450	**29**	22	23	26
(*b*) Ma stars brighter than $8^m.0$,	947	20	**31**	25	24
(*c*) B0 - B5 stars brighter than $6^m.25$	713	22	**35**	25	18
(*d*) B0 - B5 stars, $6^m.26$ to $8^m.25$,	1283	20	**35**	24	21
(*e*) Ma stars, $8^m.0$ to $9^m.0$,	1004	16	**31**	**31**	22
(*f*) Long Period variables,	1003	19	15	**36**	30
(*g*) Planetary Nebulae	132	12	14	**39**	35
(*h*) O stars	70	4	30	**45**	21
(*k*) Ma stars fainter than $9^m.0$,	730	9	24	**48**	19
(*l*) Galactic Novae,	90	15	10	**52**	23

REFERENCES—PART I—CHAPTER II

Author.	*Publication.*	*Subject.*
Seares and van Rhijn,	*Mt. Wilson Cont.* No. 301.	Number of stars.
H. Shapley,	*Harvard Coll. Obs. Circular*, No. 226.	Numbers and spectra.
H. Shapley,	*Harvard Coll. Obs. Bulletin*, No. 792.	Density of distribution.
A. S. Eddington,	"Stellar Movements and the Structure of the Universe,"	General.
W. W. Campbell,	"Stellar Motions,"	General.
Various Authors,	"Splendour of the Heavens."	General.
Bok and Bok,	"The Milky Way,"	Galactic rotation.
R. J. Trumpler,	*Publications Ast. Soc. Pacific*, **57**, 244.	"The Motions of the stars."
Russell, Dugan and Stewart.	"Astronomy"	General.

CHAPTER III

BINARY STARS, VARIABLE STARS AND NOVAE

THE VISUAL BINARY STARS

THE surveys of double star observers, such as the Herschels, Dawes, Dembowski, the Struves, Burnham, Hough, Hussey, Aitken and others, enabled the last-named astronomer to make a statistical review of the data for pairs which are sufficiently far apart on the sky to show as separate stars in our telescopes and yet be within limits of angular separation which suggest physical connection. A brief summary of Professor Aitken's conclusions is given below.

Adopting limits of angular separation according to the formula log separation (seconds of arc) $= 2{\cdot}6 - 0{\cdot}2\,m$, where m is the combined stellar magnitude of the components, which gives a range of from 250″ for $1^{m}{\cdot}0$ to 2″·5 for $11^{m}{\cdot}0$, his counts led him to the conclusion that one star in every eighteen brighter than $9^{m}{\cdot}0$ is visible as a double star within the resolving power of the largest modern telescopes. The significance of this in regard to real physical connection between pairs is brought out by the fact that if all the stars down to this magnitude were scattered at random over the sky, the chances are that in not more than about six or seven cases would two stars be as close as 10″ apart.* Aitken's limiting value for a combined magnitude of $9^{m}{\cdot}0$ is 6″·3. Of the stars catalogued 83 per cent have a separation of less than 2″, 62 per cent less than 1″, and 29 per cent less than 0″·5.

The proportion of stars that are double is ascertained to be greater in Milky Way regions than in the rest of the sky; and that this is not merely a perspective effect, due to greater extension of the stellar system in the Galactic plane, is shown by the fact that the ratio of close to wide pairs is not greater there than in higher latitudes. Professor Aitken also considers that the increase which is observed in numbers as angular separation diminishes is a real augmentation in the number of physically close pairs with smaller orbital dimensions. With regard to distribution by spectral types, the following refers to nearly 4000 pairs, classifying them by the spectra of the

* It has been remarked by A. Berry ("History of Astronomy," p. 342), that the odds against two stars of the magnitudes of the components of Castor (of which magnitudes he assumes there are 50 and 400 respectively in the sky), being by mere chance as close as the 5″ of arc which divides them, are more than 300,000 to one against.

primaries where the types of both stars are known, and, if not, by the composite spectrum of the two stars.

Table 13

Spectra of Double Stars—Percentage Numbers.

	B.	A.	F.	G.	K.	M.
Visual pairs,	8	31	29	19	12	1
All stars brighter than $8^m{\cdot}25$,	11	23	19	13	31	3
Spectroscopic binaries,	35	29	11	9	14	2

The percentages from Table 10 for all stars brighter than $8^m{\cdot}25$, and those for over 600 spectroscopic binaries are tabulated for comparison. It will be noticed that in the M and K types the visual pairs are relatively scarce as compared with the stars generally, while they are numerous in G, F and A types. This may be chiefly an effect of selection of the stars of types which are brighter absolutely, the K and M pairs being largely main sequence stars. A more valuable comparison would take into account, as far as possible, the giant and dwarf classification of the stars, so that it could be ascertained whether the differences between the relative numbers of binaries and single stars are most marked in the giant or main sequence stars. This would possibly throw light on the question of the origin of binary systems. Meanwhile it may be of value to draw attention to the apparently relatively great frequency of pairs of which the primary is a giant of F type and the companion a star of A type spectrum, the writer having found, that in pairs with a giant primary, more than 40 per cent have this spectral relationship. Shajn has also found from a study of several hundred stars with composite spectra, that the maximum frequencies of spectra are F for the primary and A for the secondary, these objects being evidently close double stars. Recently it has been shown that some at least of these pairs are composed of an F type normal main sequence star and an A type sub-dwarf of a density greater than ordinary dwarfs although not so dense as a white dwarf.

The number of visual pairs in which an orbital motion is known to be present, although often very slow, exceeds fifteen hundred. Orbital elements have been computed for several hundred systems, the reliability diminishing in general with increase in the period of revolution, which varies from a few years to seven hundred years. When the particulars of an orbit and the parallax are known with sufficient accuracy, the total mass of the system in terms of that of the Sun can be derived by the formula given in Part I, Chapter I.

The known values vary with luminosity and spectral type. By statistical methods, Russell has found the average total masses to vary from about 7 to 10 in giant systems of all spectral types, and in dwarf pairs to range from 5 or 6 in the hotter down to 0·7 or 1·0 in the cooler classes. This agrees very well with the values for a number of dwarf or main sequence pairs, as found directly from the formula mentioned. The average value for the combined masses of all visual binary systems is about 1·8 times that of the Sun, the fainter component being generally the less massive. The eccentricities of the orbits increase, on the average, with period of revolution (see Table 14), the mean being about 0·50 against 0·06 for the orbits of the eight major planets of the solar system. This relationship of period and eccentricity must, it is considered, have a physical significance.

As regards the frequency of companions to stars, a short investigation by Williams and Vyssotsky appears to indicate that a very large proportion of stars have distant companions. In fact, these workers conclude that the evidence already available shows the likelihood of as many physical stellar companions at a distance from their primaries of more than 1000 times the separation between the Sun and the earth, as ordinary visual close companions.

Multiple Systems

The occurrence of pairs or multiples among the stars in the Sun's neighbourhood may perhaps be taken as giving some idea of what is usual throughout the stellar system. Of the 250 known stars within about 30 light years distance from us, more than forty per cent are certainly members of binary or multiple systems, and another five per cent apparently belong to the same category ; six of the systems are triple and one is quadruple.

Within the past few years a new kind of member of a stellar system has been found from measurements, on photographs of very high accuracy, of the proper motions of certain stars. By these measurements it has been demonstrated that the binary 61 Cygni has a third component of small mass (only 16 times that of the planet Jupiter) and that 70 Ophiuchi has an even smaller attendant (about 10 times Jupiter's mass). Russell has investigated theoretically the probable physical characteristics of the former of these two bodies and considers that his results indicate a body of planetary type but with an internal constitution resembling that of a star and not of the major planets ; not hot enough at its surface to be self-luminous, shining therefore by reflected light and unobservable with present optical means. It appears quite likely that many stars may have similar attendants.

The Spectroscopic Binaries

More than a thousand stars are known to consist of two or more components revolving under their mutual gravitational attraction so closely together as to be inseparable by ordinary telescopic means, but revealed by the periodic displacement or duplication of the lines in their spectra. Elements have been derived for the orbits of about 400. In general, the known periods are short, ranging from a few hours upwards, more than half being less than 10 days, and the orbital eccentricities, which also increase on the average with period of revolution, are smaller than in the visual binaries, the computed values averaging about 0·20 (see Table 14). There is a gap between the longest periods of the spectroscopic pairs and the shortest of the visual binaries, which is probably due to observational selection, in the circumstance that the displacement of spectral lines in the slow-moving pairs is too small for discovery by that method, while the stars themselves are nevertheless too close for separate visual detection. The application of the interferometer to discovery of very close doubles may provide the means of bridging this gap, which has grown narrower as instrumental means have improved.

As shown in Table 13, the distribution of the spectroscopic pairs by spectral classes shows a preponderance in the B and A types, in which 64 per cent of the total are found. The spectroscopic binaries are chiefly naked-eye stars ; a large proportion of these are stars of high luminosity and more than average mass* and to this circumstance may be due the great number of stars discovered to be double by means of the spectroscope—something like two in ever five or six so far examined in this way. As Aitken says, "We do not yet know whether that percentage will hold among the fainter stars, but on the evidence before us we may venture the suggestion that perhaps the stars of larger mass, and hence presumably greater luminosity, are the ones which have developed into binary systems." The periods of revolution are generally shorter in the hotter type stars, a fact which may be partly due to their greater mass. The masses of spectroscopic binaries can only be determined in individual systems when the angle of inclination of the orbit plane to the line of sight is known (*i.e.*, in eclipsing pairs). As stated earlier, in the paragraph dealing with stellar masses, average values corresponding to a mean angle of inclination can be estimated, however ; and when these are grouped according to

* Although dwarf stars are much more numerous than giants in space generally this does not apply to any aggregate of stars brighter than a given apparent magnitude. In fact, about four-fifths of the naked-eye stars are giants or early type main sequence stars brighter than +1 absolute magnitude and at least twice the Sun in mass.

spectral type, the hotter stars turn out to be decidedly the more massive, just as has been found to be the case in the visual pairs. When the spectra of both components are visible, the relative displacements or "doublings" of the lines enable astronomers to obtain relative masses of the components, and in such cases it has been ascertained that almost without exception the fainter bodies are the less massive, the disparity increasing with the difference in brightness of the components.

The Eclipsing Binaries

There are more than 1000 of these now known, a large proportion of which are faint and therefore difficult to study spectroscopically. It will be appreciated that, given the knowledge that the light variation is the result of mutual eclipses of two stars revolving about each other, it is possible to decide from the shape of the light curve the ratios of the sizes of the stars to the diameters of their relative orbits. Surface brightness, and particulars of orbital eccentricity and inclination of the orbit plane to the line of sight can also be calculated.

If, in addition to the shapes of the light curve, curves of orbital radial velocities have been obtained, and if the spectra of both components are observable, not only relative but actual dimensions, masses and densities can be computed. Because of this the determination and classification of the spectra of eclipsing pairs is of great importance in the study of the physical character of the stars. Among the spectra observed and classified, about half are of class A, 20 per cent of class B, 15 per cent of F and the remaining 15 per cent or less are G, O, K and M. The predominance of A and B is due to their being more easily discovered because of great luminosity as a class compared with the fainter main sequence G, K and M stars. Assuming that the volume of space through which eclipsing binaries are known is that in which the A type stars are visible, there would be a very much higher number of the later types, G, K and M than has been observed, if all types in the volume could be ascertained.

A valuable addition to the methods of study of eclipsing pairs has been provided by the discovery of what is termed the "rotation effect." This is due to the effect of the eclipse of the brighter component on spectroscopically measured radial velocities. R. A. Rossiter has described the phenomena as follows, the rotation of the primary in such close pairs being almost certainly, through tidal action, in the same direction and with the same period as the orbital revolution : "The spectrum lines of a star are symmetrically broadened by the rotation of one limb away from us and of the other with equal velocity toward us, since in one case the effect is of increasing the wave length of the light and in the other case of decreasing it. The resulting displacement in opposite directions would broaden the lines, and equal opposite velocities would symmetrically broaden them. When the bright star is entering eclipse, one limb is gradually covered by the eclipsing star and consequently the lines from the bright star are fully broadened on one side only because of the velocity of the one wholly visible limb. When these lines are measured for determination of radial velocity, the centre of density of the line will be shifted toward the broadened edge, and away from the centre of the symmetrical line that would be observed if both limbs were visible. When the star is entering eclipse, the receding limb is visible, and the approaching limb is covered. The measured centre of the line is displaced toward the region of longer wave lengths, and will give radial velocities too large positively. At the centre of eclipse the lines are symmetrical, and are bisected where they normally should be. When the star is emerging from eclipse, the receding limb is covered, and the approaching limb is visible and consequently the measured centre of the line is displaced towards the region of shorter wave lengths. The radial velocities are then too large negatively."

From these discrepancies it is possible to obtain the duration of the eclipse in a manner quite independent of the curve of light variation, and also to get ratios of masses and dimensions for the component stars. From the range of the discrepancies in radial velocities, which, as explained, are due to the rotation of the primary the equatorial speed of rotation of that star can be calculated. Multiplying this by the period of rotation, which may (as stated above) be taken to be the same as the period of revolution (*i.e.*, period of light variation) the circumference and hence the diameter of the primary star may be derived. Knowing the ratios of dimensions and masses the diameters and masses of both components follow. By this method, McLaughlin has found the following for the Algol system :—

	Diameter. (Sun = 1)	*Mass.* (Sun = 1)
Bright body,	3·1	4·7
Faint body,	3·7	1·0

Distance between centres, 6,500,000 miles.

These dimensions are larger than the values previously adopted for Algol, but are no doubt more accurate, the mass agreeing very well with the average for a B8 type main sequence star such as the primary of Algol seems to be. (See Table 3).

There is a third component C, which is brighter than B. A and B together revolve round the common centre of gravity of the triple

system in a period of just under 2 years. This was discovered from the variations in the radial velocity of the centre of gravity of the system.

In many eclipsing systems the two stars are so near together that the surfaces facing each other reflect the light of the other component so strongly as to affect the shape of the light-curve. The stars have then reflection phases which are superposed on the effects due to eclipse. The shapes of the stars themselves are in such cases flattened spheroids and the total light received from the system is affected by the rotation of these spheroids which, through tidal interaction, is almost certain to be in the same direction and period as the orbital revolution. Methods of study of the light curve (assisted by the great accuracy of the photoelectric photometer, which can measure brightness to the hundredth part of a magnitude) are so refined as to be able to disentangle these effects and give values for the surface brightness of the faces which are turned towards each other and of those turned away from the centre of the system, together with the ellipsoidal shapes of the stars themselves. In fact, there are several non-eclipsing binaries known whose light variation can be ascribed to their ellipsoidal shapes alone ; but so far no single star has been found to vary because of rotation of a non-spherical shape.

Eccentricities and Periods of Double star Orbits.

The average increase of eccentricity with period, found in all classes of binary systems, is shown by the mean values below :—

Table 14

	Average Period.	*Average Eccentricity.*
Spectroscopic pairs	3 days.	0·05
	8 ,,	0·16
	14 ,,	0·22
	31 ,,	0·35
	103 ,,	0·30
	1177 ,, (3·2 years)	0·31
Visual pairs	17 years.	0·43
	37 ,,	0·40
	73 ,,	0·53
	138 ,,	0·57
	274 ,,	0·62

The foregoing eccentricities are derived from systems with known orbits. Some information may be obtained, however, regarding the shape of orbits of wide slow-moving pairs by statistical methods. It is easily seen that if all orbits of such pairs were really circular in shape, as real motion of the companion would be at right angles to the line joining it and its primary, there would be an excess of apparent motions perpendicular to this line in spite of the effects of foreshortening. This effect would be least in orbits of high eccentricity. Russell has thus found an average eccentricity of 0·61 for more than 500 pairs of average period estimated at about 2000 years and 0·76 for 800 others with average period of something like 5000 years. These are in accordance with what would be expected from the values above. The periods of binary systems increase steadily on the whole with spectral type in the order B, A, F, G, K and M, which seems to be due partly to the decrease in average mass of the stars in this order down the main sequence.

Colours and Spectra of Double Stars.

F. C. Leonard has found that in visual pairs almost invariably, if the primary is a main sequence star, the secondary is a cooler and redder main sequence star, while if the brighter star is a giant the companion is usually hotter and bluer. This is clearly brought out when the spectra are studied, but is somewhat obscured in the case of colours by the effect of contrast, which tends to make the fainter star of a pair appear bluer than it really is. These relationships of colours and spectra are so general as to provide a reliable criterion as to whether a system is composed of stars of the main sequence or has at least a giant primary. This is supported by the fact that in eclipsing pairs the fainter star has been found to be usually of the same colour as, or redder than, the brighter component whenever it has been possible to determine the spectra ; while in spectroscopic non-eclipsing binaries the fainter has been noted to be generally bluer in colour. It is probable that the former are more usually dwarfs or main sequence stars, while the latter, because of observational selection, are more often giant systems. The eclipsing pairs are found from variation of light and are thus easier to remark even when of fainter apparent magnitude.

The Variable Stars.

There is as yet no really satisfactory classification of variable stars, for, except in the case of eclipsing systems, we do not certainly know the cause of variation which would be necessary for a completely reliable scheme. The following is a provisional one which, in broad

outline, defines the chief types of the 20,000 or so variable stars now known :*

Class 1—Eclipsing Pairs.
,, 2—Cepheid Variables.
,, 3—Long Period Variables.
,, 4—Irregular Variables.
,, 5—Novae, or Temporary Stars.

Class 1—Eclipsing Pairs.—As these stars are really not variable in the sense of true physical change of light output, they have been partially dealt with in the preceding pages as double stars. Before the refined methods of modern photometry were applied, the presence of a secondary minimum was only known in the case of systems such as β Lyrae, in which the two stars are more nearly equal than usual. A light curve of this type, that for β Lyrae, is shown in Fig. 3, while that for Algol is given in Fig. 4.

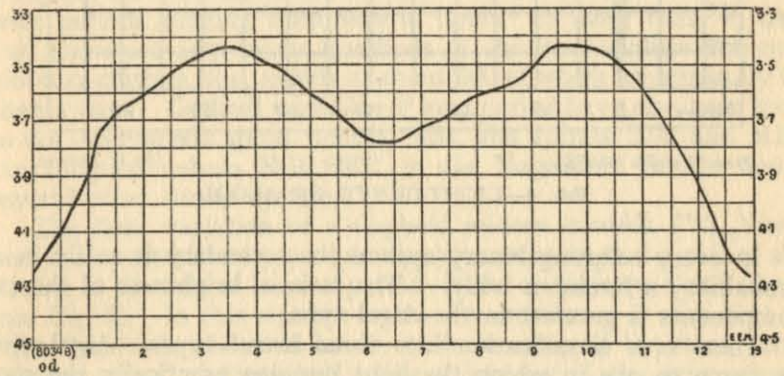
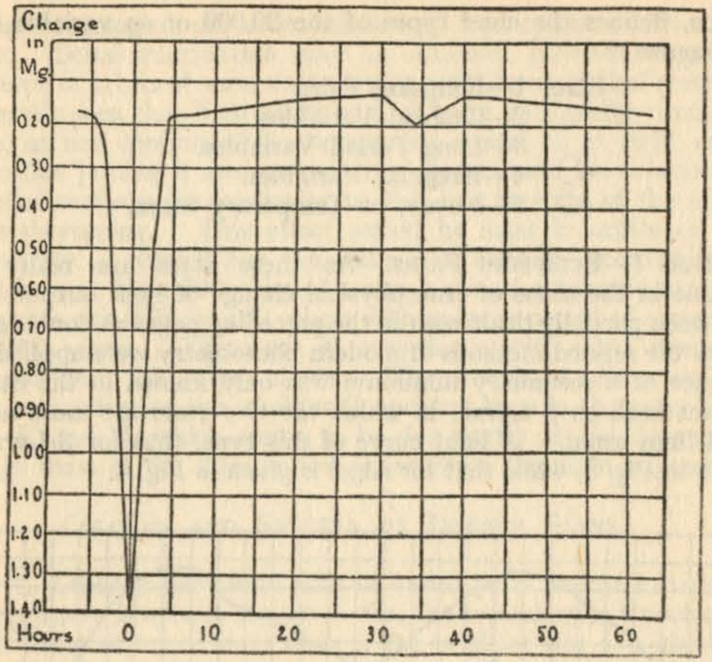


Fig. 3—Observed Light Curve of β Lyrae

The much more prominent secondary minimum is noticeable in Fig. 3, also the more gradual nature of the light changes due to the large ellipticity of figure of the two components, so that, even though the eclipse may be large or even total, the light does not remain constant at minimum. These systems generally consist of two stars of early type and low density revolving about one another nearly in contact with tidally distorted elliptical figures.

* The growth in number of known variables was very slow at first. At the beginning of the 18th century four only were known—Mira (1596), Algol (1669), R Hydrae (1670) and χ Cygni (1686). No more were found until 1782, another seven being added before the end of the century. By the end of the 19th century, about 400 were listed. The extraordinary increase to the figure quoted above, during the present century, is the result chiefly of photographic search at Harvard Observatory and elsewhere.



From "Variable Stars"). *(By C. Furness.*

FIG. 4—LIGHT-CURVE OF ALGOL.

In every eclipsing binary system the secondary is really in all probability a luminous body. The ratio of brightness of the two components is greatest in the Algol type.

There is a classification into three broad types. Algol gives its name to one in which the light remains practically the same between the minima, a relatively small secondary minimum being produced by the eclipse of the substantially less luminous secondary. Those with secondary minima of some amplitude and light curves of a more rounded form, with components elongated in shape by their mutual gravitational attraction, are called β Lyrae stars. A third type having light curves conspicuously convex upwards between eclipses, a range of secondary minimum greater than two-thirds the range of primary minimum, composed of two much elongated rather dense dwarf stars later than spectral type A0, revolving almost in contact and with periods of less than a day and a half, are given the designation W Ursae Majoris stars. The table gives some statistical data for the three divisions, based on information in "The Story of Variable Stars," by L. Campbell and L. Jacchia.

Table 15

ECLIPSING PAIRS.

Type.	*Number.*	*Amplitude of Variation.*	*Commonest Period.*	*Range of Periods.*
Algol,	800	Up to $4^m{\cdot}0$	2 to 3 days	0·2 to 9883 days.
β Lyr.,	140	Rarely exceeds $1^m{\cdot}0$.	$\frac{3}{4}$-day	0·5 to 199 days.
W Urs.,	120	Average $0^m{\cdot}65$	$\frac{1}{2}$-day	0·2 to 1·3 day.

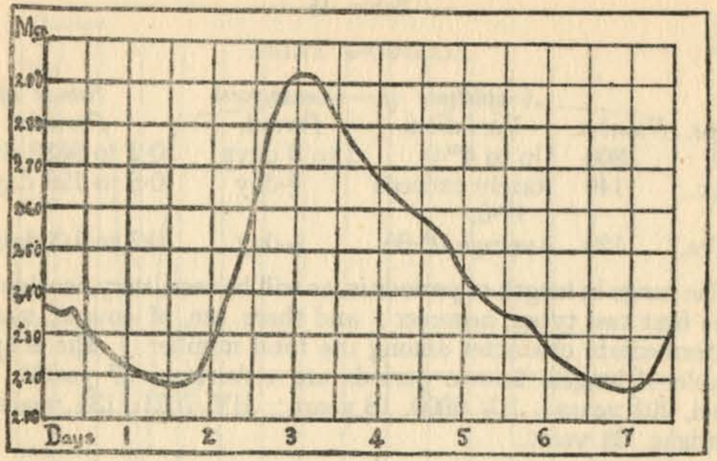
The range in length of periods is, as will be seen, very considerable in the first two types, however; and there are, of course, systems of intermediate character among the total number. The eclipsing variable of longest known periods are ϵ Aurigae, 27 years; V V Cephei, 20½ years; HV 6990, 18 years; HV 7021, 13½ years and ζ Aurigae, 2⅔ years.

CLASS 2—CEPHEID VARIABLES.—These stars are named after δ Cephei, the best known of the type. There are about 1250 known, with periods ranging from several hours* to more than 40 days, and there are also many hundreds of similar variables known in globular clusters, the periods of about 600 of which are generally less than a day. Cepheid variables of long period have also been found in the Andromeda spiral nebula, M31, the spirals M33 and M101, the irregular nebula NGC 6822, in the Magellanic Clouds, and in several other stellar systems.

The light variation of a Cepheid seldom exceeds $1^m{\cdot}2$ (visual) and is characterised by a rapid rise to maximum and a rather slow decline in the case of stars of period similar to the type star δ Cephei (see Fig. 5). In this star the increase to maximum is such that the light doubles in about 30 hours, while in many of the short period "cluster type," of about half a day or less period, the light actually more than doubles in 30 minutes. A progressive change with the length of period in the characteristics of the curve was found by Professor Hertzsprung. For periods of about 2-3 days, and also for those 10-12 days, the curve tends to be symmetrical, but progressively unsymmetrical (as in δ Cephei) between these two groups.

The radial velocities are also variable in the same period as the light, with the maximum velocity of approach occurring at about the same time as, or later than the maximum light; and the maximum velocity of recession at about the light minimum. According to Joy of Mt. Wilson Observatory there is, however, a lag of the velocity curve, with respect to the light curve, which increases with

* About the shortest period known is 100 minutes for a star in the constellation Pyxis which varies from $14^m{\cdot}5$ to $15^m{\cdot}8$, and there is one of even shorter period (C Y Aquarii) of 88 minutes.



From "Variable Stars"). *(By C. Furness.*

FIG. 5—LIGHT-CURVE OF DELTA CEPHEI

This curve is typical of those of "Cepheid" variables. It shows a rapid rise, followed by a slower fall of light, and these changes are repeated indefinitely with perfect regularity.

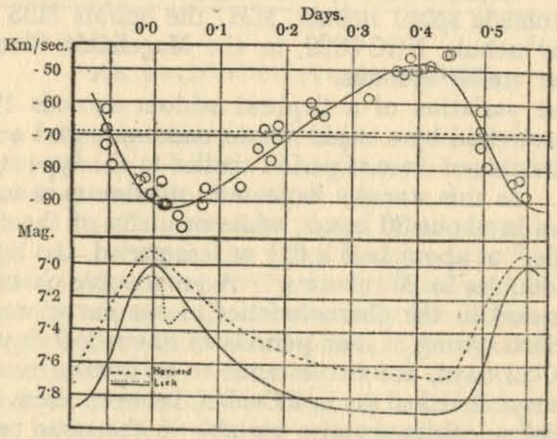


FIG. 6—VELOCITY AND LIGHT CHANGES OF A SHORT-PERIOD CEPHEID.

The lower curves represent the changes of light as observed at two different Observatories. The upper curve shows the corresponding velocity of the star or its atmosphere, as revealed by the spectroscope. The lowest point on this curve indicates the maximum speed of approach, which is seen to coincide very closely in time with the star's greatest brightness, as shown in the lower curve. The reverse holds good for the time of least brightness. This correspondence shows that the variability of the Cepheids is intimately connected with motion of some sort.

period from zero to a considerable fraction of the period ; and there are relations between length of period and amount of light variation, and length of period and range of radial velocities, so that as periods increase from about 1 day to 45 days the photographic light change varies from about $0^m{\cdot}6$ to $1^m{\cdot}8$, and the range of radial velocity from 20 to 33 miles per second.

The spectra range from A to K type with increase in length of period. They also alter during the period of light variation in the case of the individual star, by about one spectral type. This alteration indicates a higher effective temperature at maximum than at minimum, and this is shown also by a greater range in the photographic than in the visual magnitude changes.

It will be convenient to summarise here the characteristics which are observed to vary in a general way with length of period.

Range of period, from about one to 45 days.

Spectral types, from A to K.

Shapes of light curves, symmetrical at 2-3 days and 10-12 days, unsymmetrical otherwise.

Change of brightness, 0·6 to 1·8 photographic magnitude.

Ranges of radial velocity, from about 20 to 33 miles per second.

Lag of velocity curves with respect to light curves, from zero to a considerable fraction of periods.

One of the most remarkable discoveries of modern times is that the luminosities of Cepheid are fairly closely related to the period of variation. This, the Leavitt-Shapley Period-Luminosity Law, is due initially to the work of Miss Leavitt on the variables in the smaller Magellanic Cloud, and later mainly to Dr. Harlow Shapley, who showed from parallaxes derived by various methods (chiefly proper motions in the nearer objects) that this relationship holds for Cepheids in all parts of the sky, including the globular clusters. The Table gives the relationships.

The absolute magnitudes are "median" values, *i.e.*, the arithmetical means between the brightest and faintest absolute magnitudes of the average star of the period tabulated :—

Table 16

THE PERIOD-LUMINOSITY RELATION

Period (days)	*Absolute magnitude (photographic)*
0·5	0·0
1·0	– 0·4
5·0	– 1·4
10·0	– 1·9
20·0	– 2·6
50·0	– 3·5

It will be obvious that such a relationship must be very significant in any theory of Cepheid variation. It is also of great importance from another aspect, as when once the period of any Cepheid is known its luminosity follows and consequently a good estimate of its distance, from the formula $M = m + 5 + 5 \log \pi$, (see Appendix A), however far it may be away from us.

The lengths of periods of Cepheids are very regular, although there have been indications that they may change periodically or progressively, particularly in the case of those of short duration; but a study over a long interval of time will be necessary to deal satisfactorily with the matter.

CLASS 3—LONG PERIOD VARIABLES.—These are of low temperature spectrum, chiefly of M*e* (see Appendix B) types, with a number of S, R or N type. Their periods range from about 100 to more than 600 days, with a marked concentration in the interval 200 to 400 days. The longer periods are associated jointly with the later spectra (in the M type the range is from M1*e* to about M8*e*, with increase of period) and with the largest amplitudes of variation. The variation of brightness is about three to over eight magnitudes, averaging about five magnitudes. The variation bolometrically, as measured at Mt. Wilson with a thermo-couple and the 100-inch reflector is, however, very much less; the variation in heat output in χ Cygni is only about six-tenths of a magnitude as against eight magnitudes visually, and in *o* Ceti 1·3 magnitudes bolometric, corresponding to 4·5 magnitudes visually. The bolometric range is therefore similar to that of the shorter period Cepheid variable in which, owing to higher effective temperature, bolometric and visual magnitudes are more nearly the same. The periods of the Long Period stars are not regular; maxima or minima may be some weeks before or behind their expected times. A few stars have even shown definite changes in length of period: R Hydrae, from 500 to 400 days in 280 years, and R Aquilae 350 to 300 days in 80 years, are two examples.

From study of their proper motions and radial velocities, Gerasimovic has found a relationship between period and visual absolute magnitude as below. It will be noted that the relation is the reverse of what has been found for Cepheids.

Period (days)	*Absolute Magnitude.*
90 to 250	− 2·3
251 to 340	− 1·1
Greater than 340	+ 0·3

Wilson and Merrill also find the same relation, which is connected with the average spectral types; in the M variables, M 1*e* for the short period to M8*e* for the longer period stars. With the S*e* type variable the relation is from absolute magnitude −2·2 for about 150 days period, and −2·7 for 175 days, falling off at 450 days or thereabouts to +0·6. When the motions of these Long Period variables are referred to the stars in the Sun's vicinity they are found to trend towards a point at right angles to the Galactic centre as in the case of the high-velocity stars. The mean space velocity is about 46 miles per second, but this ranges from higher to lower values with increase in period of variation.

About 1300 variables of the type are known; 90 per cent have M type spectra, the remainder being of S, or R or N types. All have bright emission lines in their spectra.

Classifications of these variables, by the shape of the light curve have been made by Phillips, Turner and Leon Campbell. The classification of Phillips is by means of elaborate harmonic analysis of the light curves of more than 80 stars from which two groups were derived. A later classification by Campbell of nearly 120 light curves, all reduced to a uniform scale longitudinally and vertically for purposes of comparison, shows a regular progression from those with broad maxima and narrow minima to those of wide minima and steep narrow maxima. Seven progressive types are somewhat arbitrarily fixed by him. There is a steady increase of period in his II to VII types, which means that the stars with broad

Table 17

CAMPBELL'S CLASSIFICATION OF LONG PERIOD VARIABLES

Type.	*Average range in visual mags.*	*Aver. period in days.*	*Description of Curve.*
II	3·8	234	Max. fairly broad: min. narrow.
III	4·3	280	Symmetrical; nearly a sine curve.
IV	4·9	273	Max. somewhat narrower than min. Rise slightly steeper than fall.
V	5·5	341	Max. still narrower than min. Rise rather steeper than fall.
VI	5·0	348	Max. much narrower than min. Rise somewhat steeper than fall.
VII	4·3	363	Broad min.; steep narrow max. Rise steeper than fall.

maxima and narrow minima have in general shorter periods than those with steep narrow maxima and broad minima. Type I does not fall into this relationship and is also different from the others, in that the maximum of the curve is somewhat irregular, showing a tendency to a double maximum. Table 17 gives the characteristics of Campbell's types, omitting as abnormal Type I (of which the average range is 3·9 magnitudes, and average period 378 days).

Seven fairly representative stars of the types are, in order, U Canis Minoris, S Ursae Majoris, S Bootis, R Trianguli, *o* Ceti, R Tauri and S Tauri.

Study of the light curve of Mira by L. Campbell and Sterne has revealed an interesting correlation. It appears that, if the time between two arrivals, on the increasing branch of the curve at an arbitrarily chosen point near half way in light between minimum and maximum ($6^m{\cdot}0$ in this case) is shorter than normal, the maximum which follows is brighter than normal; and *vice versa*. The same correlation has been found in all but four of 29 variables of the type, by C. B. Ford. By this means it seems possible to predict the approximate values of maximum magnitudes. This is considered to be more than a mere geometric property of the light curve, although the underlying cause is not clear.

Joy has made an exhaustive spectrographic study of *o* Ceti with the Mt. Wilson 60-inch and 100-inch reflectors, and a number of similar Long Period stars have been studied with much the same outcome. Joy's results for Mira are given here in some detail as indicating the observed surface phenomena of the class. The spectrum varies with the light of the star. Bright high-temperature iron lines are seen at maximum, and although at minimum there are no emission lines, those of hydrogen appear soon after and reach their maximum at maximum light of the star. Low-temperature bright lines of iron, magnesium and silicon appear after maximum is well past. The elements most prominent in the absorption spectrum are iron, vanadium, chromium, manganese, calcium and magnesium. Titanium bands vary with the light of the star, but the lines of that element are weak. The bands give the same radial velocities as the absorption lines of the spectrum. The striking feature of the radial velocities from the dark lines is their regular variation in a curve resembling the star's light curve, opposite in phase to that of the Cepheid stars, since the maximum recessive velocity in Mira occurs at maximum and the greatest velocity of approach at minimum. Previous observers had thought the radial velocity from absorption lines constant, but when observations are made at all stages the variation is found to be from +40 miles per second at maximum light to +32 miles per second at minimum. The bright lines of the spectrum give a velocity curve which shows outward motion relative to the absorption line curve, except at light minimum, when the difference is zero, the greatest difference being 12 miles per second 56 days after maximum light. The intensities of the bright lines at their maximum depend on the magnitude of the star. From certain lines in the spectrum an absolute magnitude of −0·3 is obtained for the normal visual magnitude at maximum of 3·5. (See Appendix D). This gives a parallax of 0″·017, and with the angular diameter measured by the interferometer, 0″·056, a linear diameter of 307,000,000 miles and a surface brightness 7·5 magnitudes (1000 times) fainter than that of the Sun. It was estimated by Joy that the temperature varies between 2300°K and 1800°K. Measurements by radiometer at Mt. Wilson show a change in heat output, which would be explained by a variation of 15 per cent in diameter. Owing to the very great effect on visible radiation of variation of temperature at the range mentioned, the change in light, between 6 and 7 magnitudes, is very much greater than the alteration in bolometric magnitude, which is about one magnitude only, *i.e.*, the Long Period variables really change very much less in total energy output than in light output. It has also been found that the energy maximum occurs about 50 days (or, say a seventh of the period) later than the light maximum, at a point when the visual brightness has declined by $1^m{\cdot}5$, or to a fourth of the maximum brightness.

It will be noted that the change in bolometric magnitude is not very different from that of the Cepheids.

The observed drop in magnitudes visually in the Mira type is, however, greater than that calculated from the bolometric change; and this discrepancy has been attributed to selective absorption by the bands of titanium oxide, and perhaps also obscuration by clouds of particles of that substance formed at minimum.

The change in spectral type from A to K with lengthening period of Cepheids is continued in the Long Period variables to M type in a systematic and probably significant manner.

CLASS 4—IRREGULAR VARIABLES.—There are some variables which do not vary regularly. They are very diverse in characteristics and include such quasi-periodic stars as Betelgeuse and *α* Herculis; SS Cygni, U Geminorum and SS Aurigae, stars ordinarily faint which suddenly rise two or three magnitudes and then fade gradually; and R Coronae Borealis, RY Sagittarii and SU Tauri, which remain for long periods at a fairly constant brightness, suddenly fading several magnitudes and varying irregularly until they regain brightness.

In the case of Betelgeuse the radial velocities, the apparent angular diameter (as measured by the Mt. Wilson interferometer), and the light variation all seem to vary together in a most suggestive way; according to Pettit the light curve has a chief period of about $5\frac{3}{4}$ years with a range of $0^{m}\cdot 4$, and there is an irregular period, of from 140 to 300 days with a range of $0^{m}\cdot 5$, superposed. Stebbins finds that the light maximum precedes the maximum radial velocity of approach by about 0·8 years.

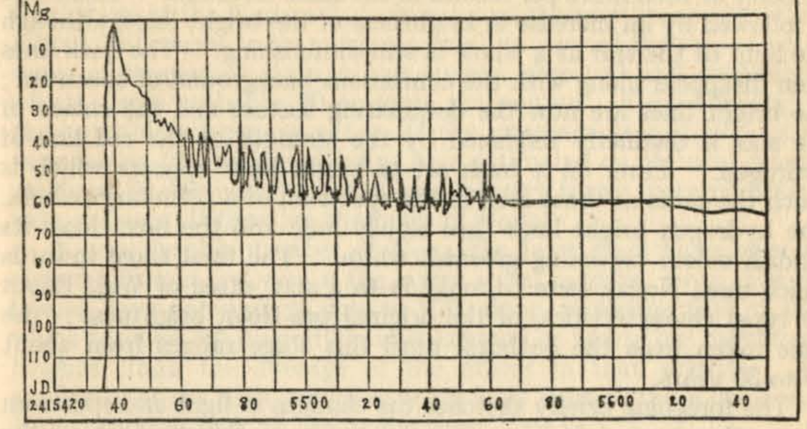
In SS Cygni two distinct forms of maximum are known, the long and the short, and there is sometimes a third anomalous type. These maxima are usually in the order—short, long, short, long; but the anomalous form sometimes interrupts the series. R Coronae has a peculiar spectrum of about G0 type and is situated in rather high Galactic latitude, the others of its class being in low latitudes.

The star η Argus is an irregular variable which is now of about 7th or 8th magnitude, but blazed up in 1843 to nearly $-1^{m}\cdot 0$, that is to about the same as Canopus. It has a peculiar spectrum with bright lines and is situated in a nebula. It (and SS Cygni, U Geminorum and SS Aurigae) should perhaps be classed with the novae or temporary stars. Such parallaxes as have been obtained, although small and rather unreliable, suggest that the Irregular Variables are super-giant stars even brighter than most of the giant Long Period stars; the mean absolute magnitude is about -2. A considerable number of faint irregularly varying stars have been found in the region of the Orion nebula M42. These appear to be dwarf stars, even allowing several magnitudes for absorption of light by nebular material, of about $+5$ absolute magnitude on the average.

Stebbins and Huffer have proved by photo-electric observations that most red giant stars show slight variation of up to three or four tenths of a magnitude (see page 93). There is, however, a type of non-periodic variable of which eleven are known, named after the best-known member of the class, T Tauri, and these are evidently main sequence stars of F5 and G5 type. They are associated with dark or bright nebulosity in or near the Milky Way dark clouds. Five of them have been found to be double stars with companions of the same order of brightness as themselves.

As Campbell and Jacchia state ("The Story of the Variable Stars," page 116), it is difficult to conceive of a really irregular phenomenon in Nature, and "it is possible that these 'irregular' stars appear to be so mainly because we have not been able to analyze the complicated processes which concur to make them vary as they do."

Class 5—Novae or Temporary Stars.—Well over 100 stars of the type known as Novae have been observed (exclusive of the objects appearing in certain of the spiral nebulae), more than 70 of which have appeared in the twentieth century. A rather typical



From "Variable Stars"). (By C. Furness.

Fig. 7—LIGHT-CURVE OF NOVA PERSEI, 1901.

This curve shows the very abrupt initial rise of light, amounting to over twelve magnitudes in a few days. Then comes the fall, rapid at first, but more gradual later. The remarkable series of undulations during a part of the fall is clearly shown, but the latter part of the curve is much more smooth. The vertical lines indicate intervals of ten days.

light curve of a bright Nova is given in Fig. 7. This shows the exceedingly rapid rise to maximum.

It is now believed that the final magnitude is generally about the same as the magnitude before the outburst, but irregular variation of light seems common in these later stages. The rise, amounting to from ten to fifteen magnitudes, usually takes place in less than a week. At this stage the colour is white and the spectrum, at first apparently continuous, soon becomes similar to that of a giant type A star with dark lines of hydrogen, iron, titanium and calcium all displaced towards the blue end, the displacement varying as the wave length and being best explained as due to a shell of gas moving out from the centre of disturbance. The star then begins to fade and becomes yellowish in colour, bright companion lines to the dark lines appearing on their red side. These bright lines rapidly broaden and show complex structure but are not displaced from the normal positions of the lines identified with the absorption companions. After a few days, some of the lines, particularly those of hydrogen, show a second dark companion displaced towards the violet to a greater extent than the first dark lines. We may then have present in the same spectrum lines displaced by an amount corresponding to a velocity towards us of more than 500 miles per second, and others of the same substance apparently giving a velocity of 1000 miles per second in the same direction. This stage is followed by an increase in brightness of the bright lines, although the light of the star as a whole is still diminishing. The dark lines then disappear along with the continuous background of spectrum; the bright lines are now the dominating feature and the colour of the star is distinctly reddened by the strength of the red line of hydrogen. Later on a fresh set of bright lines appears which is much the same as those seen in the spectrum of a planetary nebula. The hydrogen bright lines then slowly fade and the nova loses its reddish colour becoming greenish white. The final stage towards which most Novae seem to move is to a star, often of Wolf Rayet (O type) characteristics, of the original pre-Nova brightness; the time taken from the outburst until this stage ranges from about 10 to 30 years.

The foregoing briefly sketches the changes in light and spectrum of a rather typical Nova. There have been objects, such as the Novae in Aquila (No. 4), Aurigae and Herculis, which had a different kind of light curve with a sudden rise but a long flat maximum, and there have also been some of intermediate character.

The Galactic distribution has been referred to earlier, and it is interesting to note that it is somewhat similar to that of the planetary nebulae, apparently lending some support to the suggestion that these objects may be the relics or residues of novae. The light output at maximum of Novae is known to be very great. By various methods, including direct parallax measurement for some of them, combination of proper motions and radial velocities (based on certain fine absorption lines not affected by the large displacements described earlier), intensities of interstellar lines, and in several cases by means of the measured angular expansion of ejected nebulosity, the radial velocity of which is assumed to be that given by the spectroscopic measurements of the bright bands, a mean absolute magnitude at maximum of $-7{\cdot}0$ has been derived which D. B. McLaughlin has found is the average of a range from -8 to -3 according to the rate of decrease of light from the maximum, the stars that fade quickest being the brightest.

It seems probable that the initial luminosity before outburst is of the order of $+5$ absolute magnitude, and that possibly a sub-dwarf type of star has been concerned. But in the opinion of other investigators the original star may have been of a more normal type.

In the case of a number of bright Novae (Persei 1901, Aquilae 1918, Cygni 1920, Ophiuchi 1919, Pictoris 1925 and Herculis 1934) nebulosity has been observed to expand from them. Nevertheless it does not seem very likely that planetary nebulae are thus produced, as the ejected nebulosity thins out and seems to disappear in most cases. Besides this, the velocities of expansion of planetaries shown

by the spectroscopically measured radial velocities, are much smaller than those of the Nova nebulosities; and the number of planetaries (about 150) seems to be much too small in view of the rate of occurrence of temporary stars in our system, observed and unobserved, which seems probably 20 or more per annum. Even allowing for the probable temporary nature of the existence as such of a planetary nebula (the average life has been estimated on physical grounds as about 30,000 years) there should be very many more planetaries than are seen, if they are the relics of Novae.

A considerable number of Nova-like faint stars have been observed in about a dozen of the larger spiral nebulae, more than 150 having been noted up to date in M31 alone, including that of 1885, which reached 7th magnitude at maximum or nearly ten magnitudes brighter than the average of the others in that system. The similarity of the light-curves of these faint stars to those of Galactic Novae showed that all are of the same class.

The 1885 Nova in M31 was the forerunner of more than 50 of an even brighter kind found in external galaxies. The average ordinary Nova is 50,000 times as luminous as the Sun, but these "Supernovae," as they have been called, have often a maximum absolute magnitude of about -15 or 100,000,000 times the Sun's light. Several very bright Novae in our own system, namely, those of the years 1054, 1572 and 1604, were almost certainly of the Supernovae class, the luminosity of which is often comparable with that of the entire stellar system in which it is found. The observed radial velocities of ejection are of an order ten times greater than those for ordinary Novae; and it seems possible that these bodies differ (to quote the Gaposchkins) "only in brightness and radial velocity from a Nova—that is, the phenomena differ in scale rather than in kind. Possibly we may regard them as Novae that have developed from giant, rather than from dwarf stars. The frequency of Supernovae [according to Zwicky, one per average galaxy per 600 years and therefore] perhaps about a ten-thousandth of that of ordinary Novae, may well represent the relative commonness of the giant and dwarf stars from which they originate." On the other hand, Hubble has pointed out that the Supernovae appear in all types of galaxies, including the ellipsoidal where no very bright giants or supergiants are noted.

As stated above, Supernovae often reach a maximum of the order of -15 absolute magnitude or 100,000,000 times the Sun's luminosity. It seems, however, that this order of brightness applies only to one of two groups of Supernovae. In Group 1, the light curves are similar in their light decrease to that of an ordinary Nova, but the spectra have extremely broad emission bands that appear earlier than the narrower bands of the ordinary Nova. Supernovae of

Group 2 reach maxima of the order of −12 or −13 absolute magnitude, or about 10,000,000 times the Sun's luminosity; they have conspicuous "shoulders" on the descending branch of the light curve and spectra similar to that of an ordinary Nova intensified.

REFERENCES—PART I—CHAPTER III

Author.	*Publication.*	*Subject.*
R. G. Aitken,	"The Binary Stars,"	Double Stars.
R. M. Petrie,	*Pub. Ast. Soc. Pac.*, **54**, 195.	Composite spectra and sub-dwarf stars.
E. T. R. Williams and A. N. Vyssotsky.	ditto **54**, 260.	Distant Companions.
Aa. Strand,	ditto **55**, 29.	Small Companion to 61 Cygni.
H. N. Russell,	ditto **55**, 85.	ditto
R. A. Rossiter and D. B. McLaughlin.	*Astrophysical Journal*, **60**, 15.	Rotation Effect.
F. C. Leonard,	*Lick Obser. Bulletin*, 343.	Spectra of Double Stars.
P. Doig,	*Monthly Notices, Royal Astronomical Society*, **82**, 372.	ditto.
L. Campbell,	*Harvard Reprint*, 21.	Classification of long period variables.
A. H. Joy,	Mount Wilson Contributions, 311.	Study of Mira Ceti.
L. Campbell and L. Jacchia.	"The Story of Variable Stars."	Variables and Novae.
C. & S. Gaposchkin,	"Variable Stars,"	ditto.
P. W. Merrill,	"The Nature of Variable Stars."	ditto.
E. Hubble,	*Pub. Ast. Soc. Pac.*, **53**, 141.	Supernovae.
C. B. Ford,	*Popular Astronomy*, **50**, 535.	Light Curves of long-period variables.

Part II—The Nature of a Star

CHAPTER I

A STAR'S SURFACE AND SURROUNDINGS

THE theory of a star's surface usually held until a generation or so ago involved a photosphere, or light-emitting outer layer, which was supposed to be composed of clouds of solid or liquid incandescent particles of substances with high temperatures of volatilization, such as carbon. Later research showed that even the surface temperatures are usually too high to permit of the existence of matter in any but the gaseous state. A star's surface therefore consists of intensely hot gas, having a nearly transparent atmosphere shading gradually into a photosphere of gases opaque enough to obstruct radiation from the interior layers and to emit a continuous spectrum.

The brightness of a star's photosphere varies from 200 times that of the hottest part of the carbons in an electric arc in the B type, to 10 times in a G type, down to one-third in an M star. In the case of the Sun, the energy which is being radiated is equivalent to 4,700,000 horse power continually falling on the earth's surface per square mile. According to the theory of relativity, energy and mass are interchangeable, so that one can legitimately speak of a pound of heat just as a pound of iron. Viewed in this way the Sun is radiating 4,200,000 tons of heat per second.*

The Sun is the only star which can be studied in detail. The radiation which comes from the middle of its disc is found to be more intense than from the limb. This is because the rays from the regions of the limb start on the average from higher and cooler levels; the path of the rays from the same real depth below the photosphere is longer at the limb than at the centre, thus causing more effective absorption. This explains also the falling off in brightness of the Sun's disc at the limbs and also the redder colour corresponding to cooler temperature which is found there. "Darkening" at the limb exists also in the stars, as is shown by studies of eclipsing binary systems.

* In fact, it has been calculated that the mass of the radiated stellar energy contained in the volume of space which can be studied with the 100-inch Mt. Wilson reflector is equivalent to that of something like 1000 galaxies of stars.

Approximate temperatures for matter in the Sun's surroundings can be calculated by Stephan's Law (see Appendix C). Just outside the photosphere a body coated with lamp-black (and therefore a nearly perfect absorber and radiator) would normally have a temperature of about 5000°K, while at a height above the photosphere equal to the Sun's radius the temperature would be nearly 2900°K. The solar atmosphere and immediate surroundings are therefore necessarily gaseous and the same remark will probably apply to all but the coolest type stars, at any rate for the atmospheres and adjacent matter, the temperatures being usually above those of volatilization for even the most refractory materials. The phenomena of the corona, chromosphere and spots are probably persent at least in stars of type similar to the Sun, but there is as yet no means if studying these for even the nearest or largest star. For a detailed description and explanation of these solar features the reader should consult such works as Abbot's "The Sun."

Atomic Structure and Spectra

To follow the modern ideas of the constitution of stellar atmospheres as revealed by spectral analysis, it is necessary to have in mind at least a simplified theory of atomic structure. In the last forty years it has been shown that although the chemical atom is generally a remarkably stable unit of matter, it is not indivisible, as was thought by the pioneers of atomic theory. Pieces can be broken off, so to speak, and these pieces are found to be identically the same whatever element is concerned, and are taken to be charges of negative electricity or "electrons." The atom as a whole is electrically neutral and consists of a central body called the nucleus, with a charge of positive electricity ; this nucleus containing nearly the whole of the mass of the atom, surrounded by a number of negative electrons conceived of as attracted by the nucleus and moving about it in orbits like a complicated kind of miniature solar system. The positive charge of the nucleus is exactly balanced by the negative charges of the electrons, making the result neutral electrically. The nucleus is believed to be very small, less than 10^{-12} inch in diameter, the outer electron orbits which correspond to the overall size of the atom, being perhaps twenty thousand times as large or about 10^{-8} inch in diameter. The nucleus is very probably built up of positive units of electricity, "protons," and neutral units, "neutrons," bound closely together, except in the case of hydrogen ; the nucleus in that element is composed of a proton only.

In the normal atom the total charge of positive electricity in the nucleus is exactly equivalent to the total negative electricity in the satellite electrons, and one element differs from another in the amount of this electricity, or therefore in the number of electrons. This number (the "atomic number") for hydrogen is one, for helium two, for lithium three, and so on up to 92 in the case of the heaviest element found naturally, uranium.* Many atomic characteristics may be explained on the theory that the electron orbits in the more complex atoms are arranged in successive layers, or shells, each composed of orbits larger than the last.

At high temperatures the atoms move about with great velocities, colliding with one another and loading each other's electrons with energy which raises them to higher level orbits temporarily. When they leave these orbits to lower ones they simultaneously give out pulses or *quanta* of radiation, the wave-lengths of which are related to the difference in energy between the two levels. If an outer electron is actually removed as a result of high temperature and agitation among the atoms, the atom is said to be singly "ionised" and multiply ionised if two, three, or more electrons are lost ; atoms with electrons removed are positively charged as a result. What used to be called "arc spectra" of substances are produced by neutral atoms, the "spark spectra" by ionised atoms. There is thus a definite difference of origin between the two resulting in almost as great a spectral distinction as that between two different elements. Indeed the spark spectrum of any element strikingly resembles in general appearance the arc spectrum of the element of next smaller atomic number. For example, the spectrum of ionised magnesium is very like that of sodium. Since both have eleven electrons outside the nucleus, and only one outside the completed shells, the inference is obvious that the general nature of a spectrum depends on the number of electrons remaining in the atom outside the complete shells (see Fig. 8).

Atoms are ionised at sufficently high temperatures in the absence of electrical disturbance. As temperature increases in a gas the average energy possessed by the atoms gets greater. A proportion of the atoms (increasing with temperature) loses electrons, and if the ionised atoms could be kept clear from these free electrons, ionisation would go on until the atoms were all ionised and no neutral ones left. Sooner or later, however, each ionised atom, or "ion" meets and captures an electron, becoming neutral again.

High temperature and the consequent agitation among the atoms favours ionisation ; high density, on the other hand, provides a better chance of neutralisation of atoms owing to the atoms and electrons being closer together. The proportion of atoms ionised therefore depends on a balance between temperature and density,

* Elements of even higher atomic number (Neptunium and Plutonium, etc.) have been produced artificially in atom-splitting processes.

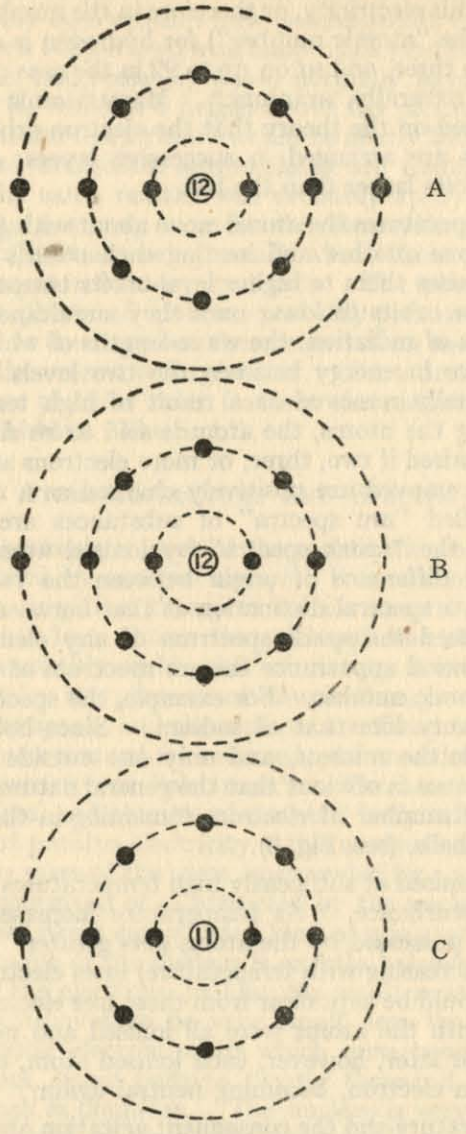


FIG. 8—IDEAL STRUCTURES OF ATOMS

(A) Ordinary atom of magnesium. (B) Ionised atom of magnesium. (C) Ordinary atom of sodium. (Diagrammatic). The number at the centre represents the positive electric charge on the nucleus. In all ordinary atoms it is the same as the number of surrounding electrons. It will be noticed that ordinary magnesium differs from ionised magnesium only in the number of electrons, and ionised magnesium differs from ordinary sodium only in the central charge.

and the spectra are consequently largely dependent on these two physical conditions.

The temperature at which ionisation takes place is different for the various elements. It is comparatively low for such as calcium, but it is very much higher for helium, greater energy being necessary to remove an electron.

Significance of the Spectral Sequence

The linear nature of the spectral sequence, *i.e.*, the fact that there is a definite series of gradations between the spectral types, shows that there is probably one chief physical cause, others producing merely minor differences. Differences in chemical composition as the primary cause of differences in spectra are definitely ruled out since in that case the properties of the various elements could vary independently giving, in stars of the same general types, says strong iron lines and weak sodium lines, or the reverse ; but this is never found.

This principal cause is undoubtedly temperature in the stellar photospheres and atmospheres, which entails different degrees of "excitation" or ionisation of atoms, with the consequent differences in obsorption lines. Taking the series O, B, A, F, G, K, M, we find : in O stars (temperature about 30,000°K) most of the lines produced by multiply ionised atoms, even helium being ionised. In B stars (20,000°K) and A stars (10,500°K) the degree of ionisation diminishes steadily. In Type F (7400°K) lines showing the presence of neutral atoms appear, while in Type G (5200°K for giants, 5800°K for dwarfs) and K (4000°K for giants, 4700°K for dwarfs) the neutral or ordinary spectral lines predominate. Finally, in M (3100°K for giants, 3300°K for dwarfs) bands due to molecular compounds appear and the neutral atom lines are very strong.

Elements in the Sun and Stars

Out of the 92 elements found on the earth there are 31 which show no identified lines in the solar spectrum. It does not follow, however, that these elements are really not present in the Sun. Only a tiny fraction of the Sun's mass, that in the layer above the photosphere (the "reversing layer"), produces lines in the spectrum and there are also many elements whose principal spectral lines lie in ultra-violet regions of wave length to which the Earth's atmosphere is opaque (wave lengths less than λ 2900).*

* Seares refers to this as follows, "The amazing performance of atmospheric ozone still goes on. Equivalent in amount to a thin shell three or four millimetres thick at sea-level pressure, it still effectively blocks practically all radiation on the short-wave side of λ 2900."

Elements such as bismuth, radium, tantalum, thorium and uranium, all with great atomic weights, are not represented by lines so far identified, and this is probably due at least partly to their being so low in the Sun's atmosphere as to be practically absent from the reversing layer. There is therefore no sufficient reason for believing that any of the elements are not present in the Sun.

The order of relative abundance of the twenty most common elements shown in the solar spectrum is as follows :—

Table 18

Hydrogen	Nickel
Helium	Sodium
Oxygen	Aluminium
Magnesium	Zinc
Silicon	Manganese
Nitrogen	Chromium.
Sulphur	Cobalt
Iron	Potassium
Carbon	Titanium
Calcium	Copper

Hydrogen and helium account for slightly more than 98½ per cent and oxygen and magnesium for one per cent, leaving less than half of one per cent for the remainder in the table. Most stellar atmospheres have much the same composition as the Sun's. Some have a relatively large amount of particular items such as carbon, strontium, silicon or sulphur ; but these are mainly stars either of low or very high temperatures. The relative strength of the lines of different elements in stars of the same general type is very similar, and it is now considered that, in general, uniformity of composition of stellar atmospheres is an established fact. The observations on abundance refer only to the stellar atmospheres ; but as marked differences of internal composition might be expected to affect the atmosphere to a noticeable extent, it is unlikely that any fundamental internal differences exist as regards the elements which are actually present.

Pressures in Stellar Atmospheres

The temperature at which a spectral line reaches its maximum intensity depends on the pressure in the atmosphere of the star. It is possible to find this temperature by observation (see Appendix C) and from it, and the observed line intensity, the pressure can be calculated. By these studies it is found that theoretically the

pressures in the reversing layers should be extraordinarily low, ranging from about one-thousand millionth of an atmosphere at the top to one ten thousandth of an atmosphere at the bottom. The average distance through which the atoms would move between successive encounters (the "mean free paths") can be calculated to be about 1300 yards and a twentieth of an inch respectively for these two theoretical densities, which refer to the average on giant stars, and should be increased for dwarfs where the atmosphere is much less extensive, the pressure gradient more rapid and the total range probably somewhat less. The smallness of these values is due to the outward pressure of radiation, which in a star is capable of supporting atoms against gravity. Strictly speaking, perhaps we should not refer to "pressure in the reversing layer," for pressure, like temperature, has a gradient throughout a star. This gradient is steep at the centre, but becomes smaller towards the star's surface, where radiation pressure and gravitation are of the same size approximately, till in the tenuous outer regions there is no appreciable pressure gradient, and atoms are almost floating freely. Such tenuity makes it at first difficult to understand how the photosphere of the Sun, for instance, is opaque and definitely bounded at the limb. The explanation is to be found in the extraordinary opacity of ionised gases. As ionisation is greater at the higher temperatures, the opacity is strongest in the hotter stars being, for instance, 20 times as great in the atmosphere of the A-type star Sirius as in the G-type Sun. In giant stars, with more diffuse atmosphere, the opacity is less but there it is also greater in the giant of higher temperature.

Differences in Spectra of Giants and Dwarfs

The effective temperature of a giant is lower than that of a dwarf, but the pressure in the atmosphere of the latter is relatively greater. The effects on ionisation of atoms and the spectral consequences are therefore to some extent compensatory, but fortunately not in complete detail ; on this depends the possibility of "spectroscopic" parallax determination (see Appendix D). The net residual result of these two factors is that elements in which ionisation is easy are more ionised in giant stars than in dwarfs, and those in which it is difficult are less ionised. This is what is found in the case of the lines used for determination of absolute magnitude and parallax.

There is good reason to believe that a greater quantity of gaseous material can be seen through when density is low, *i.e.*, comparing a giant and a dwarf of the same temperature, the quantity of matter above the photosphere in the former is greater, although at lower pressure and density. Spectral lines are therefore stronger in giants, and because of the lower density, sharper also. These characteristics are exhibited most strongly in the *c* stars mentioned in Part I, Chapter I.

Bright Lines in Stellar Spectra

Hundreds of stars are known of types ranging from O*e* (or O6) to A2, and probably there are more than 350 brighter than about $8^{m}{\cdot}0$, in which this phenomenon is noted. The ratio of numbers of stars with bright lines to others of the same spectral type increases steadily from about one in eight (O type) to one in more than 6000 (A type) and the proportion is also highest amongst the stars of brightest apparent visual magnitude. It therefore appears likely that the more luminous stars tend most strongly to develop bright lines, which is supported by their concentration to the Galactic zone, a feature of distribution of the more luminous stars. The most conspicuous lines are always those of hydrogen, with sometimes a few lines of helium and various ionised atoms and in many cases these bright lines vary in intensity. The Long Period variable stars also shew variable bright lines of hydrogen, iron, magnesium and silicon. The existence of bright lines brighter than the continuous background means that the star's atmosphere or gaseous surroundings has a more intense emission in the particular wave length than the photosphere. That this is due to the possession of extensive gaseous atmospheres has now been demonstrated for the hotter type stars mentioned. They appear to have envelopes which are expanding, rotating or pulsating. The Wolf-Rayet stars (O type with bright lines) have continuous spectra with wide bright lines superposed ; and there is probably a high temperature central star with a rapidly expanding gaseous envelope the material of which is continually being restored by atoms ejected from the star.

There are other bright line hot stars such as the P Cygni and the B types, all stars of high luminosity. They also are considered to have large atmospheric envelopes. The B type eclipsing variable β Lyrae has, it is suggested, an extended envelope sursounding the two components, which is produced and maintained as the result of the passing of a stream of gas from the more massive to the less massive component ; some of this goes round the latter star and partly back to the primary, but the remainder goes right past the primary and swings round to form a large envelope surrounding the system. The bright lines in the spectra of the Long Period variables are probably due to periodic pulsatory outbursts of hotter internal gases. One important recent development is the discovery that many close binary systems have tenuous rings of hydrogen and other gases, which revolve round the hotter and more massive component in the same direction as the binary system itself. This has been found by study of the bright lines in the spectrum which originate in this ring. The larger, cooler, less massive and less dense component first occults that half of the rapidly rotating edge-on ring which is approaching the observer, then the whole ring is completely or nearly covered so that no bright lines, or much fainter ones, are visible, the primary star being itself covered, and the approaching side is then uncovered and the receding side alone is covered. It has been found that in eclipsing systems in which the eclipse is total, one out of every four examined shows observable features due to a ring of the kind. There seems good reason to believe that many single bright-line B-type stars have similar rings, the existence of which is of course not discoverable in a similar way. The binary systems described may perhaps be regarded as a further stage in the development of a binary of the β Lyrae type.

The Widening of Spectral Lines : Stellar Rotation

The lines in the spectra of stars are broadened by various factors. There is a natural width due to the fact that the atoms do not radiate at one sharp frequency, and there are Doppler effects of toward and from components of movements of individual atoms in a heated gas and of large-scale movements of masses of gas in the stellar atmosphere, and also magnetic and electric effects. In some stars there are broadenings caused by the motion to and from the observer of the limbs of the star in its rotation. These indicate much faster rotational speeds than the Sun's. For example, Altair (α Aquilae), a main sequence star of about $+1{\cdot}7$ absolute magnitude appears to have surface limb velocities of 160 miles per second ; and this is a minimum value as the axis of rotation is probably inclined to the line of sight, no rotation effect being observable if the axis is in or near the line of sight between the star and the observer, the maximum effect being if the axis is at right angles to that line. The diameter of this star is about twice that of the Sun, and the period of its rotation must be about nine hours or less, or not as much as a sixtieth of the Sun's. The stars for which rotation has been noted in this way are B, A and F type, but practically none of G type. They are generally of about $+2$ absolute magnitude corresponding to masses about twice that of the Sun. The reason for this restriction of observed rotation to a somewhat limited range of stars is not clear.

The Constitution of a Giant Star's Atmosphere

The lines in the spectrum of a star are the result of absorption at different levels by gases of various temperatures and densities.

Some idea of the constitution of a giant star's atmosphere may be got from study of an eclipsing binary such as ζ Aurigae. Here there is a K 4 supergiant of very large diameter (200 times that of the Sun) and small density, which, every 973 days eclipses a B 8 companion less than a sixtieth of its diameter for a period of about 60 days. Before the eclipse the spectrum is a composite of the two, but as the small star goes behind the large one, its light is progressively absorbed by the latter's atmospheric envelope and the spectrum changes ; the B star fades away, like a planet setting in a smoky atmosphere and disappearing before it reaches the horizon. The spectrum at each state of the eclipse of the smaller star thus gives an idea of the physical conditions in each layer of the K star's atmosphere. The sequence observed is as follows. At the beginning when the B star is shining through the primary star's upper atmosphere, strong, narrow lines of hydrogen and lines of ionised calcium are photographed. The next lines to show themselves are of ionised metals with the hydrogen and calcium lines strengthening ; and as the denser strata are traversed neutral lines of metals become prominent. Eventually the light of the B8 star is extinguished and the K4 supergiant spectrum remains. As the smaller star reappears gradually, the phenomena occur in the reverse order. It should be noted that solar eclipses show that hydrogen and calcium extend higher than any other element in the Sun's atmosphere also. But perhaps the most remarkable thing about the phenomena observed is the extraordinary slow rate at which the giant's atmosphere gets thinner. It is calculated that for a star like ζ Aurigae the force of gravity at its surface is such that the density of its atmosphere should get greater inwards much more quickly than it seems to. The Sun's atmosphere is also more tenuous than it should be in the same way ; and the cause of the phenomenon is still unknown in both cases.

REFERENCES—PART II—CHAPTER I

Author.	*Publications.*	*Subject.*
Miss Cecilia Payne,	"Stellar Atmospheres,"	General.
Russell, Dugan and Stewart.	Young's "Astronomy,"	General.
Abbot, G.	"The Sun,"	Solar.
Goldberg and Aller,	"Atoms, Stars, and Nebulae."	General.
O. Struve,	*Observatory*, 66, 208,	"Gaseous Rings in close Binary Systems."

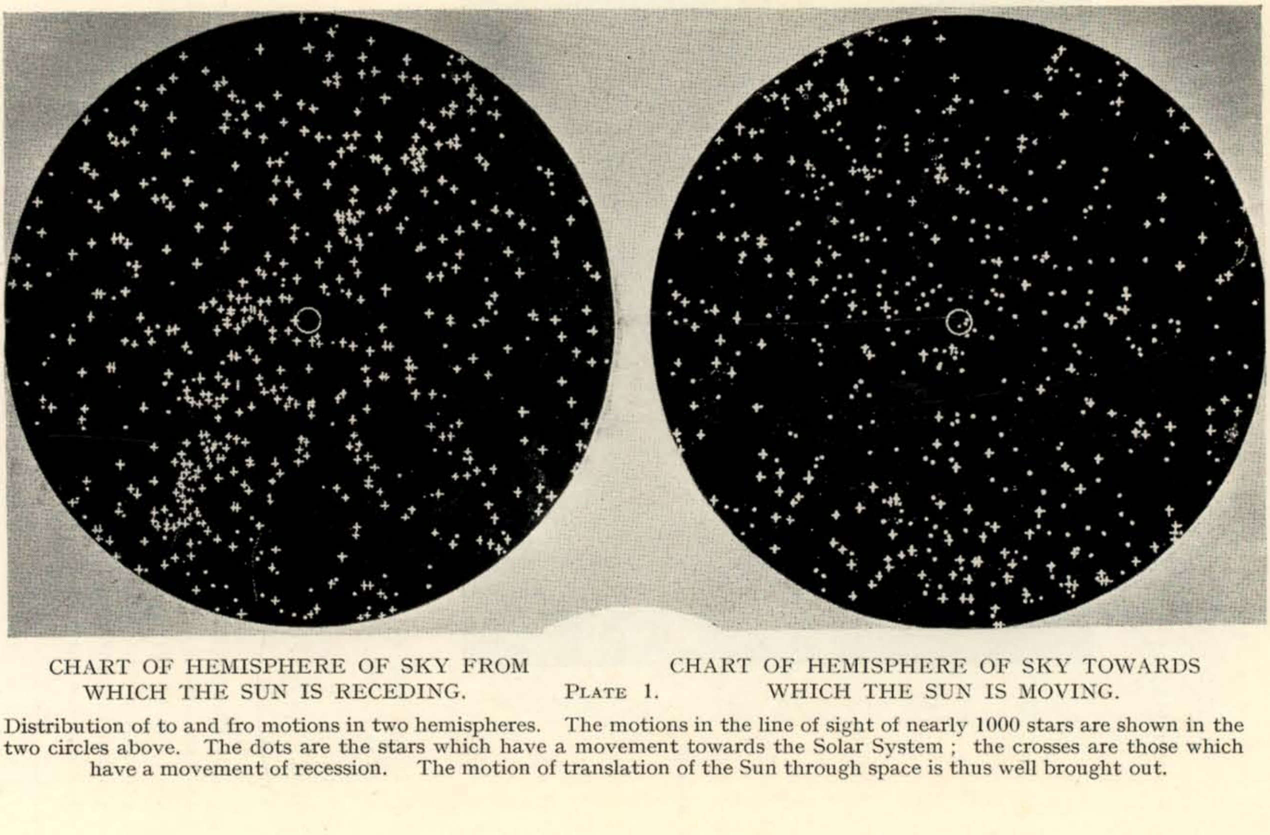


CHART OF HEMISPHERE OF SKY FROM WHICH THE SUN IS RECEDING.

PLATE 1.

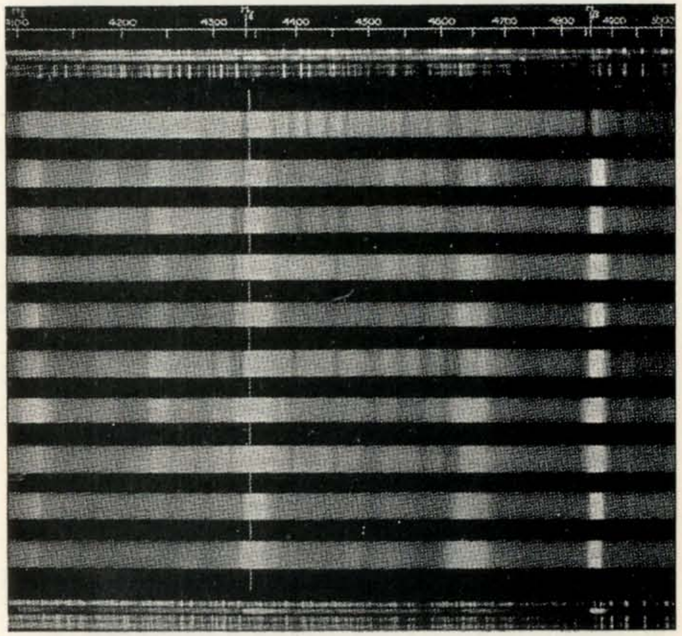
CHART OF HEMISPHERE OF SKY TOWARDS WHICH THE SUN IS MOVING.

Distribution of to and fro motions in two hemispheres. The motions in the line of sight of nearly 1000 stars are shown in the two circles above. The dots are the stars which have a movement towards the Solar System ; the crosses are those which have a movement of recession. The motion of translation of the Sun through space is thus well brought out.

Plate 2—THE SPECTRUM OF NOVA GEMINORUM, 1912.

Photographed at the Cambridge Observatory, March 16-April 29, 1912.

No. 1 Mar. 15
,, 2 ,, 15
,, 3 ,, 20
,, 4 ,, 22
,, 5 ,, 26
,, 6 ,, 28
,, 7 ,, 30
,, 8 Apr. 1
,, 9 ,, 3
,, 10 ,, 8
,, 11 ,, 29
,, 12 Mar. 30



Nos. 1 and 12 are stationary enlargements, showing the comparison spectra of iron.

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 *α 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.

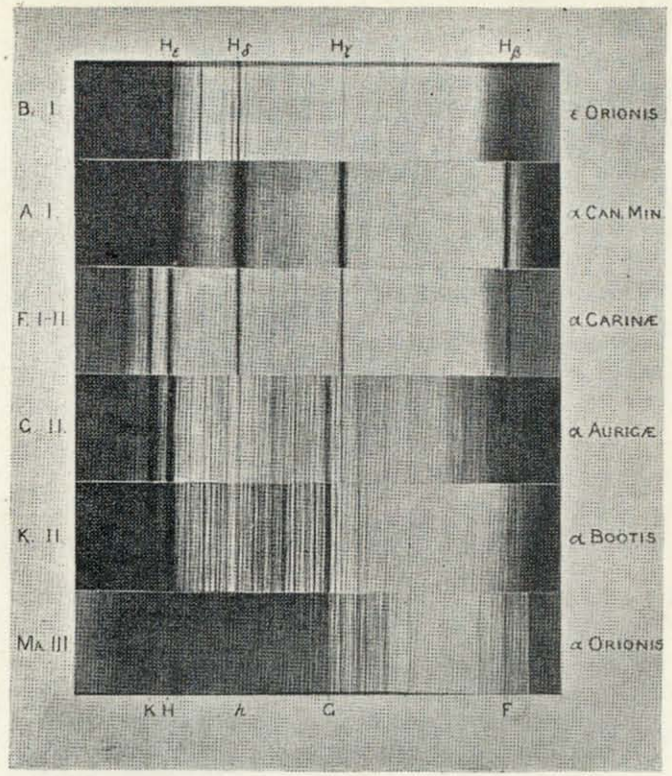


Photo by) (*Harvard College Observatory.*

Plate 3.—THE CHIEF TYPES IN THE HARVARD SPECTRAL SEQUENCE.

Nearly all the recorded stellar spectra belong to the types represented in this photograph, or to intermediate types. The characteristic lines of the B type are those of helium. The strong hydrogen lines in the A type spectrum gradually become weaker in the succeeding types. The increasing complexity of the spectra after the F type is due to the appearance of many lines of the metals. Class M spectra are not well represented in the region represented here.

Photo by) *E. E. Barnard.*

PLATE 4.—THE GREAT STAR CLOUD IN SAGITTARIUS.

Taken with the Bruce 24-inch photographic doublet. Shows distant star clouds in the direction of the centre of the Galaxy, and some luminous nebulosity and dark obscuring clouds closer to us.

PLATE 5a—PLANETARY, NGC 7293.

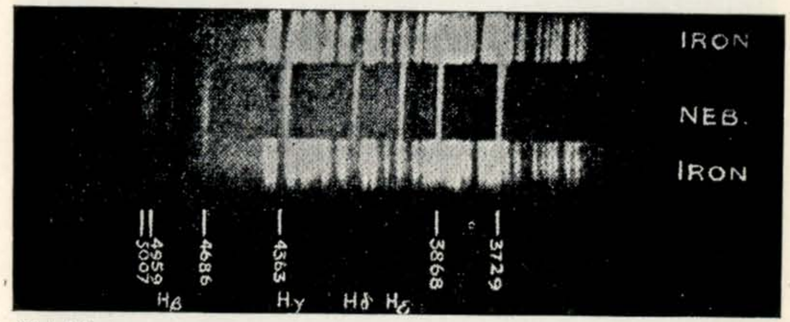


Photo by) *(Max. Wolf.*

PLATE 5b—SPECTRUM OF THE DUMB-BELL NEBULA, NGC 6853.

This is a gaseous emission spectrum on a faint continuous background.

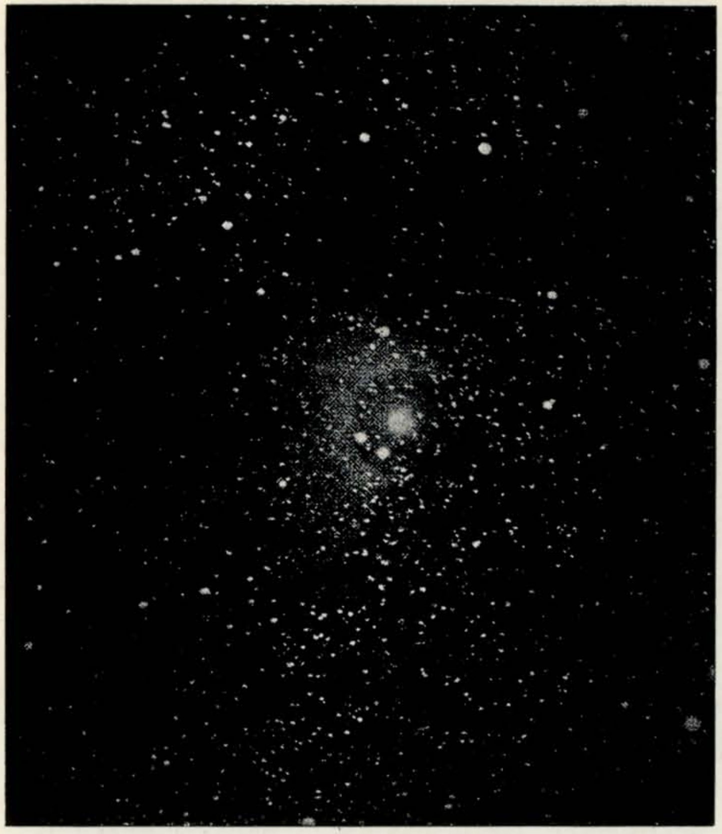
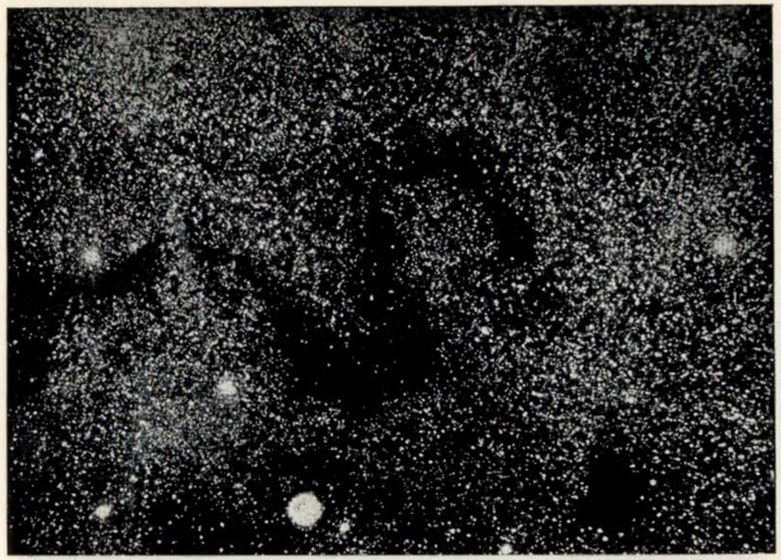


PLATE 6—NEBULA ROUND THE STAR ν SCORPII.

Photographed by Professor E. E. BARNARD with a Six-Inch Portrait Lens.

The nebulosity surrounding the star stretches for some distance, but its illumination is probably due to the star itself and possibly one or two other bright ones in the vicinity. The dark halo round the star is a photographic effect, owing to the plate used being unbacked.



From) ("*Astrophysical Journal*"

PLATE 7a—OBSCURING CLOUDS IN OPHIUCHUS.

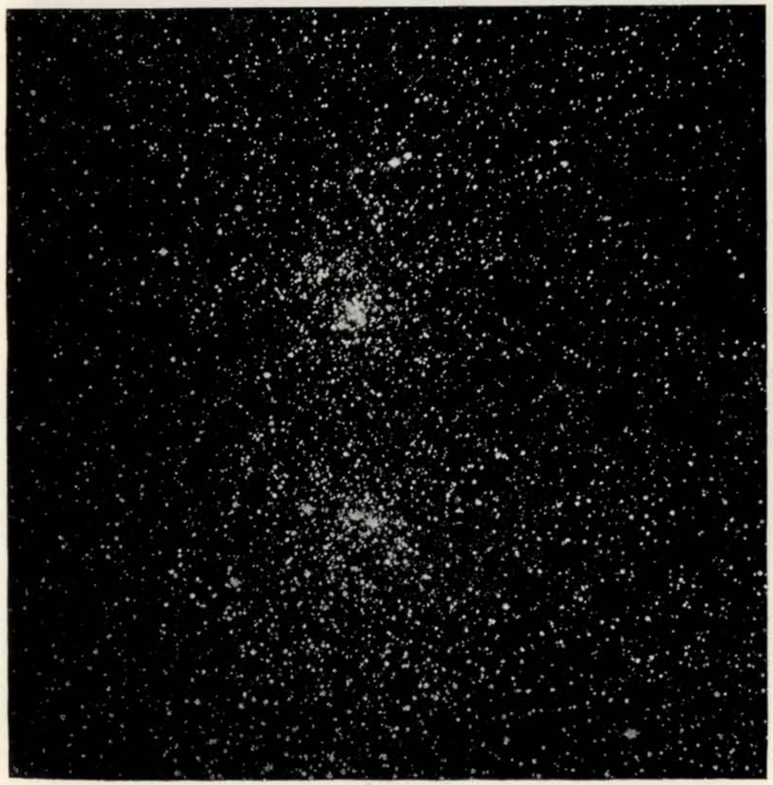


PLATE 7b—THE DOUBLE CLUSTER, NGC 869,884, IN PERSEUS

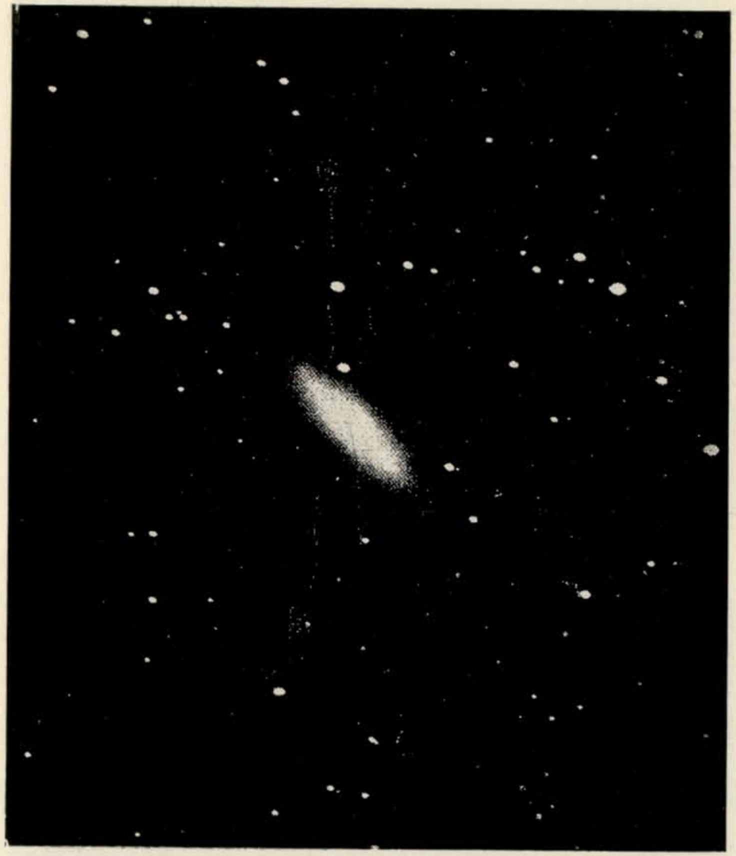


PLATE 8a—THE E-TYPE NEBULA, NGC 3115.

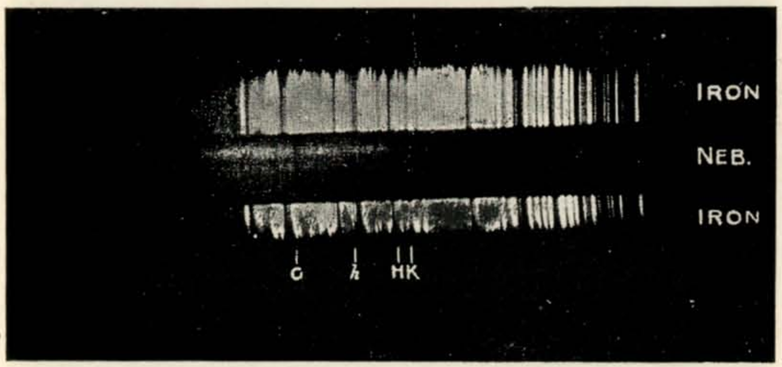


PLATE 8b—SPECTRUM OF THE NUCLEUS OF THE SPIRAL NEBULA M81, NGC 3031.

CHAPTER II

A STAR'S INTERIOR

AT first sight it might appear unlikely that astronomers could find out much if anything about the interior of a star. Direct study is confined to spectroscopic and visual survey of the conditions at the surface, whereby we are able to ascertain the chemical composition and to some extent the physical state of the layers near the surface. It is here that the mathematical physicist comes to the aid of the astronomer and assists him to penetrate, so to speak, into the inside of a star. In an outline work of this description, however, it is only practicable to give a general idea of the theories of radiation and internal constitution, commonly accepted, and this will now be done.

As a star is a mass of intensely heated and highly ionised gas, it is possible, for a particular distribution of internal density, to calculate internal temperature and pressure at any point. This is because the properties of a highly-ionised gas are very close to those of a "perfect" gas, where, subject to some modification due to pressure of radiation, the following relationship holds :—

$$T = \frac{pm}{R\rho}$$

T being temperature, *p* pressure due to atomic, etc., movement (gas pressure), *m* the mean "molecular"* weight, *R* a constant which is the same for all gases and ρ the density. From the assumed law of density, pressure follows, while *m* cannot be much different from unity at the temperatures concerned.

This value *m* is near unity because of the stripping from all atoms of nearly every one of their satellite electrons. For instance, a hydrogen atom is split into two parts, a proton and an electron, with an average molecular weight of 0·5 ; helium is divided into three with the value 1·33 (= 4÷3) ; carbon into seven, value 1·71 (= 12÷7) and so on. Even with the heaviest element, uranium (which is probably very scarce in a star) the value is only 2·56 (= 238÷93). As the proportion of hydrogen (and helium) in a star is high, the mean molecular weight is thus never much different from unity. In the case of the Sun, the proportion of hydrogen is considered to be

* The term "molecular" weight is used, although only atoms, electrons, etc., are concerned, as it gives the mass divided by the number of particles resulting from ionisation.

about a third to a half and *m* is usually taken as 1·0. In the stars generally, the proportion of hydrogen is believed to vary from about an eighth to three-fourths, and *m* from 1·3 to 0·6.

The detailed structure of the material of a star may be summarised briefly as follows. The central regions consist of a mixture of bare nuclei and dissociated electrons. As we pass from the centre the temperature falls, and atoms which are more nearly complete as regards their satellite electrons are encountered. Close to the surface the atoms are probably quite complete except for some of their outermost electrons. At the surface itself, especially in the cooler type stars, molecules may even be found, such as those of titanium oxide, zirconium oxide, cyanogen and magnesium hydride, which appear in M, S, N or R type stars.

From the foregoing it will be seen that, for an assumed law of internal density, it is possible to calculate the values of temperature and pressure at all points which will give a condition of mechanical equilibrium throughout the star's interior. The true law of density is not easy to determine, but various models have been assumed for the purpose of calculation to see if they satisfy observational results.

The rate of escape of radiation through the star's photosphere (the measure of luminosity) may be calculated, the flow being carried almost entirely by radiation, with only a small fraction due to convection. This rate depends on the opacity of the stellar material which can be approximately derived on reasonable assumptions. These assumptions rest on the idea that absorption and re-emission of the energy throughout the star are primarily due to processes involving interaction between the ionised atoms and electrons, which are more frequent the more of these particles there are in a given volume (*i.e.*, the greater the value ρ/m), but less likely to happen when they are moving fast (T great).

In the calculation of the luminosity of a star the chemical composition is involved in two ways. The heavier elements mean greater opacity, and the average molecular weight depends, in the manner already indicated, on the constitution. But, except for hydrogen, and to a lesser extent helium, the result is nearly independent of the constitution, as the increase of average molecular weights with heavier elements counteracts the effect of increased opacity. The amount of hydrogen or helium makes a great difference and where calculations of stellar luminosity are made, based on the proportions of these elements which seems reasonable from indications found in the outer layers of the stars, the results correspond fairly closely to the observed values.

Although various assumptions have to be adopted (which are all tested by comparison with the observed properties of the stars) the

position may be broadly summarised by the following extract from a standard work :* "The characteristics of the stars depend upon the simplest and most fundamental laws of nature, and even with our present knowledge might have been predicted from general physical principles if we had never seen a star.

The laws of gravitation, of radiation, of atomic structure, and of simple gases suffice as a basis for such prediction. . . . .

For bodies massive enough to shine, the radiation would increase rapidly with the mass, but would change but little with the diameter, the smaller bodies (for equal mass) being hotter inside, but letting only a little more heat leak out to the surface, than the larger ones ; this, however, would keep the surface much hotter, on account of its smaller area."

Radiation Pressure.

It is essential to take into account this phenomenon, which is of considerable importance in the question of stellar radiation. It is known both from theory and experiment that radiation actually has mass and momentum and exerts a pressure on any object obstructing it. A star's interior has atoms rushing about in all directions, because of high temperature, with speeds up to hundreds of miles a second, and the energy of such moving atoms constitutes a great store of heat contained in the star. This is only part of the store, however ; the radiative heat constitutes another portion. Waves of radiation are hastening in all directions inside a star. They leak very slowly into space, the history of their careers consisting in alternate absorption and re-emission by atom after atom, a process which might last for hundreds of years until the wave reaches the surface of the star to be emitted thence, the original radiation being in the form of γ or X-rays, which are absorbed and re-emitted as temperature radiation by the time they reach the surface.

In bodies heated to the temperature possible in a terrestrial laboratory, the heat is practically confined to the molecular movements, a negligible fraction being radiation. In a star, however, the quantities are more nearly equal, and because of the pressure effect mentioned above there is a force tending to assist the elasticity or gas pressure in resisting the inward gravitational pull of the material. This has to be taken into account in calculating temperatures ; its neglect has the effect of making too high the result from theory based on gas pressure only. The mathematical physicist can calculate this radiation pressure which amounts to about

* "Astronomy," Russell, Dugan and Stewart, ii., 894.

17 tons per square inch at 1,000,000°K ;

170,000 tons per square inch at 10,000,000°K ;

being proportional to the fourth power of the temperature.

The proportion of radiation pressure to the total is dependent on the mass of the star, increasing with it in a way that suggests that a maximum value of mass is determined by it, beyond which a stellar body could not exixt.

Lane's Law.

Before proceeding to an outline of recent ideas of the anatomy of a star and of its production of energy and possible lines of evolution, it is desirable that a short account of the relations referred to as Lane's Law and frequently mentioned in the literature, should be given. The first investigations of the probable distribution of temperature inside a star were made in 1870 by J. Homer Lane, followed later by Ritter, Lord Kelvin, Emden, Schwarzschild and others. Lane reached the apparently paradoxical result that a star by losing heat and contracting actually grew hotter. A star shrinking under gravitation to half its linear size and remaining built on the same model, or "homologous" (*i.e.*, the densities at two corresponding points at any two stages remaining the same fraction of the mean density) would be eight times as dense, and the internal pressures would be sixteen times as great as the overlying material is attracted four times as strongly and its weight is held up on only a quarter of the area. From the formula connecting temperature with pressure and density, given earlier in the chapter, it will be seen that the temperature in this example would be twice as great. By such reasoning, Lane concluded that as stars get smaller they grow hotter to withstand gravitation and resist collapse. In all the pioneer work it was assumed that heat was transported from the interior to the surface by conduction or by convection currents, so that the inside was thoroughly stirred and followed a similar law of thermal equilibrium to that in the lower regions of the earth's atmosphere. As already stated, it is now clear, however, that most of the transfer of heat is by radiation and that the flow of radiation determines the distribution of temperatures. There will be a tendency to a different kind of distribution owing to the presence of some convection, which must exist as otherwise the action of gravity would produce a settling down of the heavier elements towards a star's centre, leaving very little but hydrogen to be detected in the outer layers. Such convection as does exist will be either in the form of slow circulation of matter throughout a star or of turbulent mixture, and there appears to be evidence of both types ; in the Sun, for instance, from the phenomena of sunspots, solar granulation, and eruptive prominences.

The Internal Structure of a Star.

The problem here set is to find the interior distribution of densities, pressures and temperatures, given the mass, luminosity and radius of a star, and using our knowledge of gravitation, radiation and properties of gases. A helpful idea of the distribution of density can be obtained by study of the light curves and radial velocity curves of eclipsing binaries from which rotational movements of the lines of the major axes of the orbits (the lines of apsides) and ellipsoidal distortion of shape in close pairs are occasionally derivable, such features being governed by the interior distribution of the stars' densities. This study has thus shown that there is a rapid increase of density towards the centre which was to be expected for other reasons. A recent estimate for the Sun gives a central density more than 100 times that of water, and the figures in this model for a fifth, third and half its radius from the centre are approximately 40, 10 and 1 respectively. As a star is only in a stable condition if the superincumbent mass at each point is balanced by the gas elasticity and radiation pressures, it is possible therefore, knowing mass, radius and bolometric luminosity (total energy produced) to calculate pressure, density and temperature at any given depth in the star. The central temperature is of high importance, as it is believed that it determines the rate at which energy is generated ; and the chemical composition, which, as has been already stated, affects the transparency or rate of flow of energy to the surface and also affects the central temperature, is another factor of great significance.

As described in the first section of this chapter, practically all atoms are completely ionised in a star's interior, and the average molecular weight, which depends on the proportions of elements present, has a bearing on the temperature to be found. For example, a star made entirely of nitrogen and one made of hydrogen (where the "molecular" weights of the ionised atoms would be 1·75 and 0·5 respectively), alike in mass, density and radius, would have different internal temperatures, as the nitrogen particles would require to move with greater velocities than the more numerous hydrogen particles to hold up the superincumbent layers. Consequently stars are hotter if composed more of heavy elements than of hydrogen. As a result the first estimates of central temperatures by Eddington and others, being based on a smaller proportion of hydrogen than is now considered correct, were higher, 40,000,000° or so against about half that figure.

The probable composition is estimated by a process of trial and error using various assumed proportions of hydrogen, helium and the heavier elements and calculating the rates of increase of pressure and temperature towards the centre, and the central temperature and luminosity. Different mixtures are assumed and tried out until the calculated luminosity equals that observed. In the case of the Sun with the average molecular weight taken to be 1·0, the central temperature is found to be about 20 million degrees.

With the assumption that all main sequence stars have the same interior pattern (the same model) it is noted that the central temperatures (*T*c) vary from about ten million degrees for those of least luminosity (M type dwarfs) up to thirty million for the most luminous (B and O type). The range in the amount of energy produced is very much greater. For instance, a faint star of small mass (say an eighth of the Sun's mass) emits energy at a rate per unit of mass about a twentieth that for the Sun, while each unit of mass in a star of high luminosity (say of 30 times or more the Sun's mass) may radiate several hundred or even more than a thousand times as much as a unit of mass in the Sun. Using the data of Table 3 for bolometric magnitudes (which are the measure of total radiation), and for masses, it is found that the average ratios between total radiations and masses are as follows for main sequence stars, in terms of the Sun; B0, 210; A0, 22; F0, 5; G0, 1·3; K0, 0·4; and M0, 0·06. For giant stars the values are: F0, 41; G0, 23; K0, 26; M0, 59. For supergiants the values may be as high as several thousands.

The high luminosity giant stars, if they are of the same interior pattern of structure as those in the main sequence, appear to have relatively low central temperatures; for Capella, about six million degrees has been computed and for the redder giants it is believed to be as low as a million degrees.

To summarise what are perhaps the present general ideas. Main sequence stars are composed of matter which appears to behave as a "perfect" gas throughout, with radiation pressure not large as compared with gas pressure; central temperatures are of the order of 10 to 30 million degrees with the mean temperatures about half the central value; the density at the centre is generally from about 10 to more than 100 (water = 1), the mean density is about a fiftieth or less of this, and the radiation per unit of mass ranges from about a twentieth in M type to 200 times in B-type, in terms of the radiation of a unit of Solar mass. Ordinary giant stars have similar general properties, but central temperatures are from less than 5 up to 10 million degrees, and central densities are much smaller—about a tenth as much; while radiation per unit of mass is more uniform than for the main sequence, averaging about 40 times the value for the Sun.

The Source of Stellar Energy.

All authorities are now agreed that the old hypothesis of gravitational contraction as the source of solar or all stellar radiation is quite insufficient. The age of the earth has been demonstrated by evidence based on geological and other facts and also on the uranium-lead ratio of the older rocks, to be of the order of 2000 or 3000 million years which is much greater than the maximum admissible (about 20 to 40 million years) for its parent body the Sun, on the gravitational theory. An age of at least as long seems to be required for the Sun and most stars, and therefore a much greater source of energy is apparently necessary for this prolonged period than that of gravitational energy released by contraction. Outside sources of heat, such as collision with meteoric matter, are also ruled out (at any rate as the sole means), the crux of the problem being not merely the provision for surface radiation, but also the maintenance of an internal heat sufficient to prevent collapse under gravitation. For instance, to keep the Sun in its present condition of equilibrium, a temperature gradient of from 6000° at the surface to about 20 million degrees at the centre has to be maintained, and it is clear that this cannot be effected only by supplying heat at the surface or lower end of the gradient.

Further evidence of the existence of some internal store of energy appears when we consider the rapidity of evolution required by the contraction hypothesis in the case of a giant star; Eddington calculated that a star of 11·5 times the mass of the Sun would take less than 31,000 years to develop from type M to type G and not so much as 72,000 years from M to A. Observation shows that most of the naked-eye stars are in the giant, or high-luminosity main sequence, stages; and it is not easy to believe that so many of these stars have changed from red to white in such a short period. Another indication of the internal store of energy is found in the case of the Cepheid variables, which are thought to be stars pulsating in a period depending on their densities. If there is no internal source of energy, contraction under gravitation would necessitate an increase of density entailing, for example, a shortening of the period of variation in δ Cephei of 17 seconds per annum, which is certainly not the case.

It therefore appears clear that the stars must contain within themselves the energy which is to last their lifetimes.

The store of energy must be sub-atomic, that is to say, related to the constitution of atoms and electrons. Three hypotheses have been suggested:—

(1) Radio-activity, or the breaking down of more complex atoms into simpler elements.

(2) The building up from simple elements of some of more complex atomic structure.

(3) Mutual cancellation of protons and electrons, *i.e.*, annihilation of matter.

The first of these three involves the postulating of elements of higher radio-activity and greater atomic weights than those known to terrestrial experience. Even if the Sun were made of pure uranium the radiation would be only about half what is observed and its life only a fraction of what seems likely to have been the case.

In the case of (2) what is involved may best be illustrated by the transmutation of hydrogen into helium which may take place inside a star. The atomic weight of the hydrogen atom, which is composed of a proton and one electron, is 1·008 (oxygen's atomic weight being taken as 16·00). When a helium atom is formed from four hydrogen atoms, an atom consisting of a nucleus of two protons and two neutrons, and having two electrons revolving round it, is built up. The atomic weight is 4·004, not $4 \times 1{\cdot}008$ or 4·032, as might be expected, since the mass of both hydrogen and helium atoms is practically all contained in the nuclei. There has thus been a loss of 0·028 or 0·7 per cent of the mass; the energy corresponding to this mass must have been set free during the process of combination.

The third hypothesis, unlike the first two, depends on the temperature and pressure. This is because it involves the idea of collision between a proton and an electron so that their electric charges cancel each other and nothing is left but radiation of extremely short wave length, which soon becomes transformed into longer waves of heat. Such collisions will be more frequent at high temperatures and densities. It was contended, however, that stars under such circumstances would be explosively unstable and that the hypothesis was therefore unsound. It was also urged that the interior temperatures, high as they are, are much too low to cause mutual annihilation of matter and production of radiant energy, as in hypothesis (3).

Recently hypothesis (2) has received support which has made it favoured, although details may yet require considerable revision. A possible source of the energy has been revealed by intensive study of nuclear physics. The account which follows is based largely on lectures by Sir James Jeans.

Rutherford's experiments showed that the nuclei of the atoms of light elements could be transmuted into nuclei of different chemical properties by bombardment with α-particles. At stellar interior temperatures, α-particles, which are merely the nuclei of helium atoms, are probably quite common, heat having completely removed the orbital electrons.

Atomic nuclei and the atoms generally are bombarded by α-particles and other swiftly-moving projectiles—protons, neutrons and the like. These reactions are called thermonuclear, and they are mostly very sensitive to changes of temperature, so that each reaction may be associated with a definite critical temperature below which it occurs only very slightly, but above which in torrential amounts. This critical temperature depends greatly on the complexity of the nuclei involved and it is consequently lowest—500,000° to 1,000,000°—for the simple reaction of one proton with another. In this a deuteron (positive electron and two neutrons, the nucleus of a "heavy hydrogen" atom) is liberated. This ejected positron then encounters an ordinary negative electron with mutual cancellation and the production of radiation; and the deuterons also react with protons producing helium of mass 3 and radiation.

When these processes (which take place at the first stage of a star's life following the initial gravitational contraction stage) have exhausted their possibilities, the star contracts owing to the lessening of energy necessary to keep it at its former size. This produces central temperatures of 2 to 9 million degrees, when protons may react with the nuclei of the light elements lithium, beryllium and boron; and later, there is further contraction and increase in temperatures. When temperatures at the centre of the order of 20,000,000° are reached, there is the reaction of a proton with a carbon nucleus of mass 12. The combination forms a nitrogen nucleus of mass 13, but this is only the first of a series of processes. of what is termed the "carbon cycle." The nitrogen nucleus may capture a second proton, becoming an ordinary nitrogen nucleus of mass 14, and then a third proton, becoming a nitrogen nucleus of mass 15. This may capture yet a fourth proton, but the result is not a nitrogen nucleus of mass 16; it is usually a carbon nucleus of mass 12, together with a helium nucleus of mass 4.

The foregoing description of the carbon cycle has omitted some minor processes which have no effect on the final result. The main events consist of the carbon nucleus absorbing four protons one after the other, and thereby being moved along the sequence of nitrogen isotopes* until this road comes to an end. In this way 4 protons are bound together to form a helium nucleus; all the other nuclei are unaltered. The carbon has acted as a sort of catalyst.

This transmutation may not appear to have any relation to the supply of energy for the star's radiation. But, as has been referred to above for hydrogen, there is a loss of 0·7 per cent. of mass which

* Practically all elements have varieties of their atoms identical in chemical properties, but differing in atomic weight owing to additional neutrons in their nuclei; these are termed "isotopes."

goes off as radiation of short wave ("soft X-ray") to be absorbed and re-emitted by the interior material as longer wave "temperature" radiation constituting the star's luminosity.

The various stages described are considered probably to provide the causes of luminosity of the stars as they increase in temperature, the carbon cycle being that which applies to most of the range of the main sequence. Presumably the reactions characteristic of lower temperatures take place, in minor amount no doubt, away from the centre of a star, at points where the temperature, although lower than that at the centre, is sufficient for the thermonuclear reaction in question—that is if there is any of the required element left.

A number of difficulties have yet to be overcome in connection with this attractive hypothesis and there will probably be modifications, some of them important, particularly in the case of the red giant stars and hot temperature high luminosity stars.

In connection with these hypotheses of transmutation of elements, it seems possible that, during the past history of the universe, the elements have all been built up from hydrogen with production of radiation. The fact that those of larger "atomic" number (see p. 63) are scarcer generally is consistent with this view, although an observed smaller frequency of elements with odd atomic numbers has not yet been given an explanation.

REFERENCES—PART II—CHAPTER II

Author.	*Publication.*	*Subject.*
A. S. Eddington,	"The Internal Constitution of the Stars."	General.
A. S. Eddington,	"Stars and Atoms,"	General.
Russell, Dugan, and Stewart.	Young's "Astronomy,"	General.
J. H. Jeans,	*Nature*, 1943, Jan. 2,	"Evolution in Astronomy."
G. Gamov,	"The Birth and Death of the Sun."	General.
L. Goldberg, and L. H. Aller.	"Atoms, Stars and Nebulae."	General.
A. Holmes,	*Benn's Sixpenny Library*,	"The Age of the Earth."
J. Homer Lane,	*American Journal of Science and Arts*, 1870.	"On the Theoretical Temperature of the Sun."

CHAPTER III

THE EVOLUTION OF THE STARS.

THE duration of life of a star is so long that observation of successive stages in stellar evolution in an individual star is quite out of the question ; even in the periods of geological time it is certain from geological evidence that very little change can have occurred in our Sun. Among the millions of stars, however, it is possible to select specimens which seem to represent each stage of the luminous life of a star. As the elder Herschel remarked, in connection with the nebulae and clusters : "Is it not almost the same thing whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering and corruption of a plant, or whether a vast number of specimens, selected from every state through which the plant passes in the course of its existence, be brought at once to our view ? " The task of the astronomer is to arrange in this manner the various classes of stars for which observational data have been collected, in some systematic scheme of evolution and orderly development.

A great amount of information regarding the physical characteristics of the stars, mass, density, luminosity, colour, spectrum, temperature and so forth, has been collected by various methods of research. In Russell's words, modified to allow for subsequent progress, the central problem of stellar astronomy may be formulated as follows :—From the existing data, and from all further data which may be secured by methods new or old, to deduce a theory of stellar evolution, that is, of the changes in the temperature, density, brightness, spectrum, and other observable characteristics of a star with the progress of time, and of the dependence of these changes upon such factors as mass, composition, and angular momentum of rotation. Such a theory must satisfactorily represent the observed properties of the majority of the stars, and the relative abundance of the different types.

In addition to the main problem there are those of the source of stellar energy (dealt with in a previous chapter), the origin and evolution of binary and multiple systems, and the causes of variability of luminosity.

FORMER THEORIES OF EVOLUTION.

These involved the idea that stars generally are losing heat and falling in temperature, the hottest stars being the O and B type and the coolest the M type. It seems probable that astronomers formerly did not conceive that the stellar spectrum could be produced by a body diffuse enough to act as a perfect gas and therefore supposed that Lane's Law (see previous chapter) did not apply in regard to increasing temperature, except perhaps in some very early stage of development. Bluish-white stars, such as Rigel or Sirius, were considered to be the youngest, born from diffuse gaseous nebulae, yellow stars like the Sun or Capella being further contracted under gravitation and at an intermediate stage, and the orange and red stars were thought to be passing towards a stage of extinction. Certain facts of distribution, such as the observed association of white stars with gaseous nebulae, and the reverse for the redder objects, were believed to be confirmation of this order of evolution. A progressive increase of space-velocity in the order of falling temperature was also taken as support, although it was not at all clear why velocity should get greater as a star grew older. Both of these observational data have received explanation on grounds quite different from those which were first believed in, and which were accepted by most astronomers well into the present century, leading to the use of the terms "early" and "late" for the hotter and cooler spectral types respectively.

The Giant and Dwarf Theory.

One or two investigators had, nevertheless, doubted these almost universally accepted ideas of development. The first rational theory, taking into account Lane's Law, was based on the hypothesis of maintenance of heat by gravitational contraction. A diffuse giant red star was supposed to contract and become hotter, obeying perfect gas laws until the density became so great that the molecules of the gas came nearly together. The central temperature would then reach its maximum and the star would cool down in the liquid or solid state to extinction, the surface temperature, although not passing through as great a range, following a similar course. In principle, this was a revival of the ideas of Lane and Lockyer, adapting them to the observational data of "giant and dwarf" classification, described in an earlier chapter, so that the stars could each be classified as rising or falling in temperature. Those on the rising branch of M, K, G, F, A, B sequence of spectra would be large and of low but increasing density. Those on the falling branch of the order, B, A, F, G, K, M, would be smaller and of still higher and increasing density. This theory, revived by Hertzsprung and Russell about 1913, seemed to account for all the facts, both in general and in detail. It appeared possible to show, for instance, that the highest maximum surface temperature would be reached only by the more massive stars, and this was found to be

the case for the B type. It was also thought that the stage of difficult compressibility and departure from behaviour as a perfect gas would take place at about the density of A type (about a fifth that of the Sun). The configuration of spectral types and absolute magnitudes, shown in a diagram such as Figure 1, also received an apparently satisfactory explanation. The division into two distinct classes, one of great, but of much the same order of luminosity throughout the spectral types and the other progressively fainter towards the redder stars, was to be expected. As the spectra were substantially the same, type for type, in the two groups, the conclusion was that surface brightnesses per unit of area were similar and that the difference in luminosity must be due to difference in area of radiating surface, one group of stars being of very large dimensions, the other composed of considerably smaller bodies. The diminishing size in the order M, K, G, F, A, B in the giants was counteracted by an increase in temperature and surface brightness, resulting in a fairly constant luminosity ; while in the dwarf or main sequence branch the luminosity fell off because of diminishing size and also decreasing surface brilliance.

It is now known that the theory, as outlined, is certainly not a sufficient one. The giant or ascending series may present no insuperable difficulties, but the main sequence branch is not to be explained after the manner suggested by Hertzsprung and Russell. As we have seen, the conditions of ionisation in a stellar interior are evidently such that the perfect gas laws continue to be obeyed at very much higher densities than are experienced terrestrially, the stars behaving as though constituted of perfect gas even with densities greater than those of ordinary liquids.

Present Ideas of Stellar Evolution.

It can be stated that there are not so far any very generally accepted ideas on this subject.* But for the very earliest stage of stellar evolution most astronomers take the view, which has been current during the greater part of the present century, namely, that a star begins its life as an enormous gaseous spherical mass of exceedingly small density slowly contracting under gravity. The clouds of dust and gas in the dark obscuring nebulae have been thought to be possibly the material of which stars are made ; and it has recently been suggested that any condensations in them will tend to become pressed into spherical shapes by the external pressure of radiation from surrounding stars, and that this will be assisted

* One well-known astronomer has recently remarked, "Of our present jumbled ideas of stellar evolution the less said the better." Another states that "he knew all about stellar evolution in 1923, less in 1925 and nothing at all since 1930."

by gravitational attraction of the enclosed material, with the formation of stars of low temperature and small density in a period of time calculated to be of the order of 100 million years. The interior temperature is then much too low to start up any thermonuclear processes; but when the advancing temperature gets as high as say half-a-million degrees at the centre, nuclear reactions commence which, by increase of temperature and of gas pressure, prevent further contraction.

As stated in the chapter on the source of stellar energy, the first reaction is likely to have been the one in which deuterons are involved. Following the exhaustion of the material for this reaction, contraction and heating up take place until, with central tempertures of from two to about nine million degrees, the reactions with lithium or beryllium atoms begin, and then those with boron atoms.

As these elements get used up there are more stages of contraction rapidly passed through; the radiation is derived from the energy of gravitational contraction until the central temperature reaches about twenty million degrees when the carbon cycle begins. During the stages before that cycle is active, it is considered that the star shows spectra of M, K, G and F type giant stars in succession, until arrival at central temperatures of ten to thirty million degrees brings it into the zone of the main sequence (see Fig. 1).

The most usual presentation of these ideas proposes that the deuteron reaction marks not only the ordinary red giant or supergiant M and K stage, but also probably the Long Period variable; and that the lithium and beryllium processes which occur in the G and F type giants and supergiants are taking place also within the Cepheid type of variable. The processes described entail great increase in generation of energy as they are reached at stages of higher temperature. The consequence may be that in each case there is a rather sudden expansionary state reached with accompanying cooling and therefore a temporary reduction of production of energy which creates a somewhat unstable condition. In such instances circumstances appear to be present which are likely to produce pulsating long-period or Cepheid variable stars. The boron reaction is the next stage of the F type or A type giants before they reach the main sequence.

According to these ideas, which are due to Gamov and others, a star is considered to pass through the stages described with not much enhancement of its luminosity until, when it reaches the main sequence branch, it passes *upwards* along the branch to the B type or to the O type, according to its mass, while the hydrogen atoms are being meantime used up in the carbon cycle.

When the hydrogen is exhausted there does not appear to be any source but gravitational attraction for the star to use in the production of energy (although there is perhaps the possibility of some other thermonuclear processes, not yet identified, at temperatures over twenty million degrees) and the star drops greatly in luminosity to the white dwarf stage, perhaps more than ten stellar magnitudes fainter.

Modern theory suggests that a star in its last radiating stage is a small body of extremely great density and it is considered that the white dwarfs may be in this very late part of the life of a star. Their average densities are of the order of 50,000 or more times that of water with central densities perhaps hundreds of times again as great as that. The central temperatures are, however, not thought to be very high as compared with those of main sequence stars—probably of the order of ten million degrees. The enormous densities are due to the stripped state of the atoms through ionisation; nuclei and electrons are jammed tightly together. As the volume of an atom has been calculated to be actually 10^{14} times the total of the volumes of its constituent protons, electrons, etc., complete ionisation would in theory permit of compression to densities of the order of 10^{14} times ordinary matter, which is much beyond the mean densities attributed to white dwarfs. But recent theoretical developments have shown that there is a limit to the compression, and that at that limit there will be no energy available for radiation at all, the white dwarf being thus an intermediate stage between a normal and an "invisible" star. As already stated, the source of the energy radiated in the white dwarf stage is thought to be probably gravitational contraction.

There are certain difficulties in the way of complete acceptance of these ideas of giant, main sequence, and white dwarf stars. Some of these difficulties will now be referred to.

Stars of large mass radiate so much energy per unit of mass that they must evolve and live much more quickly than lighter ones. They must, therefore, have been born at a relatively recent date, or have existed in a state of very low radiation and luminosity. Stars of large mass and very low luminosity have not been found, and a stage of small luminosity for such bodies, providing a longer life, does not therefore appear to occur.

It has been suggested that such stars may be able to collect enough hydrogen from interstellar space for nuclear reactions, enabling them to shine for a longer time. But this would appear to require an interstellar medium (see Appendix G) of greater density than seems likely; and it is moreover contended that such collection of hydrogen might lead to unstable or even explosive results.

Another difficulty is found in the need for an explanation of the spectral relationship in the components of double stars (referred to in Part 1, Chapter III). On the once current Giant and Dwarf theory of a star's evolution, this relationship appeared to be natural if stars in pairs are of simultaneous origin, and if the star of smaller mass evolves more rapidly. In that event the fainter star in the giant stage would be "earlier" in spectral type and evolving more quickly, and when the pair is in the main sequence the companion would naturally be of "later" type and be ageing more rapidly. It is true that it can be said that on the new ideas of evolution, pairs on the main sequence may both be moving upwards on the branch, the more massive and luminous star evolving the more rapidly, but a binary pair on the giant branch has the secondary of an "earlier" type spectrum (unless it happens to be on the main sequence when it is occasionally of "later" type) and therefore evolving *faster* than the primary on the new ideas, although it is less massive.

Then there is the difficulty presented by the co-existence of young giants with apparently old dwarfs in clusters, the stars of which are presumably contemporaneous in their origin.

Another matter requiring consideration is the fact that if the cooler giant stars owe their energy to terrestrially very rare elements such as beryllium, lithium and also boron, they would require to have been initially in the possession of much more substantial quantities than are found in the earth or Sun. Otherwise they would go through the giant stage so quickly by exhaustion of their supplies, that the proportion of the numbers of such giants and supergiants to the number of main sequence stars would be even smaller than it is.

It may also be remarked that although the course for giant stars, which appear to join the main sequence at about G, is clear on the sketch of evolution given above, the formation of the main sequence branch of stars hotter than G type being thus explained, the origin of the lower end of the branch is not so well accounted for. There seem to be very few stars fainter than the giants, and cooler than G type, whose joining the main sequence at the bottom end would similarly explain what will really turn out to be the most crowded part of the sequence, *i.e.*, the part composed of M and K stars (see Fig. 1). It appears, however, to be quite possible that the gap between the giant and dwarf K stars is not real, and that many stars of intermediate brightness have yet to be found (see Martin, *Observatory*, **66,** 82); and it may even prove that further investigation will show a number of intermediate stars in the gap between giant and dwarf M stars (see Jackson, *Observatory*, **66,** 374).

One apparent objection relates to the increase of a star's luminosity (of the order of 100 times) supposed to take place in passing upwards in the main sequence after that zone has been entered, which looks like a contradiction of the mass-luminosity relationship, since the mass actually becomes less (although only very slightly) in the process of energy generation now believed to be probable. The explanation given for this is two-fold. In the first place, the suggestion is made that the stellar universe may be as yet very young, with most of its stars still in their earlier stages, when mass and luminosity may be closely related; secondly, it is considered that the time spent in the upward passage through the main sequence may be rapidly passed through so that very few stars would be caught at that stage. It is believed that support is given to this idea by the fact that such stars as have been noted to be abnormally luminous for their masses are usually found in these higher ranges of the evolutionary path.

Although, as has been remarked earlier, the hypothesis of collection of interstellar matter, chiefly hydrogen, as a factor of importance in stellar evolution, is not thought a likely one in view of inadequate density of such material, it may be nevertheless worthy of further consideration on the lines advanced by Lyttleton and Hoyle. These investigators find that the rate of accretion of mass by a moving star through a medium of the kind is proportional directly to the density of the medium and to the square of the star's mass, and inversely to the cube of its velocity; and they suggest that, in regions of space where interstellar matter may be much denser than the normal, slow-moving stars of greater mass than usual would result, and that in other parts of space the more rapidly moving dwarfs would be formed. The greater velocities and smaller masses of later type main sequence stars (see Table 5) and the greater lengths of periods of later type dwarf binaries would be consistent with this. The relation of spectra of the components of binaries does not appear, however, to be capable of explanation by this hypothesis any more than by that already discussed; but the presence of early "young" giants and later type dwarfs, presumably of contemporary origin, in a star cluster, might not be so difficult to undertsand. It is worthy of remark that the idea above described appears to be somewhat like an earlier one advanced in 1918 by C. D. Perrine, that the "stars of classes A, B and O, the planetary and irregular nebulae, the novae and perhaps the Cepheid variables, are confined to the galaxy because there the matter is sufficiently plentiful to cause an increase of energy, the energy of the matter swept up being in excess of the energy lost by radiation. The direction of spectral changes in such conditions is *towards the nebulae.* In the regions (distant or near) where there is little or no cosmic matter, radiation will overpower the energy received from external sources and the direction of change will be *toward the late types.*"

Readers will appreciate, however, that the statement made at the beginning of this section, to the effect that there is, as yet, no well-established, or even very plausible, comprehensive theory of evolution of stars, is a correct one.

The Origin of Binary Stars.

There are three chief theories of the origin of binary and multiple systems, which may be stated as follows :—

1. By the chance encounter of two stars, resulting in their revolution about a common centre of gravity (the capture theory).
2. By a previous existence in the original dust cloud or nebula of independent nuclei separated by a distance comparable with those now observed in visual systems, and by subsequent condensation about such nuclei.*
3. By division of a single star into two components through centrifugal, and possibly occasionally tidal, fission, influenced by radiation pressure.

The first of these does not seem likely to have been frequent, taking into account the great distances which separate the stars in the stellar system. Calculations based on reasonable assumptions show that only about once in three billion years will there be an approach between two luminous stars within a distance equal to the radius of Neptune's orbit (see Appendix H). Another point apparently adverse to the capture theory is to be found in the relations of the spectra of the components of physical pairs, previously mentioned, which show that the companions in giant systems are bluer and in dwarf pairs redder than their primaries. This could hardly be expected to be a general rule if the origin of pairs were by capture. Methods 2 and 3 are perhaps both valid, and may be the normal ones for the relatively widely-spaced visual pairs of multiple systems and for the close spectroscopic and eclipsing binaries respectively.

It should be noted, however, that from the researches of Kuiper, a common method of origin, which he considers cannot be that of fission, is perhaps likely for both, as the distribution of lengths of major axes of orbits appears when analysed to be really the same for all classes of binary. Kuiper also considers that fission is not possible for the accepted model of a star's internal structure, or even for stars less concentrated towards the centre ; and also that if

* One of the earliest to suggest this was Laplace, without, however, any mathematical basis :—"The condensation of nebulae, consisting of two nuclei, will form stars very near to each other, revolving the one about the other like to the double stars." ("Systéme du Monde," 1796).

fission were a method of origin the distribution of the ratios of the masses of the components would be similar for all classes of binaries, which it is not.

The early stellar evolutionary process for the individual components involved in method 2 is well described in the words of W. W. Campbell, one-time director of Lick Observatory. "It will happen that there are regions of greater density, or nuclei, here and there throughout the structure, which will act as centres of concentration, drawing surrounding materials into combination with them. The processes of growth from nuclei originally small to volumes and masses ultimately stupendous must be slow at first, relatively more rapid after the masses have grown to moderate dimensions and the supplies of outlying materials are still plentiful, and again slow after the supplies have been largely exhausted. By virtue of motions prevailing within the original nebular structure, or because of inrushing materials which strike the central masses, not centrally but obliquely, slow rotations of the condensed nebulous masses will occur. Stupendous quantities of heat will be generated in the building up process. This heat will radiate rapidly into space, because the gaseous masses are highly rarefied, and their radiating surfaces are large in proportion to the masses. With loss of heat the nebulous masses will contract in volume, and gradually assume forms more and more spherical. When the forms become approximately spherical, the first stage of stellar life may be said to have been reached."

If the method of fission is after all a possible one, further evolution of close pairs sometimes produced from the larger masses formed as by method 2, might follow. This might then provide a satisfactory explanation of the frequency of B and A types among the relatively very close spectroscopic and eclipsing binaries ; the cooler type giants have not divided in considerable numbers, while the F, G, K, and M dwarf pairs are not observed in large numbers owing to lower absolute brightness.

As a result of this process of division the companion stars might be expected to be less dense than the primaries, being possibly the result of expansion of smaller masses with less gravitational contraction forces, or composed of outer and more tenuous layers of the rotating parent masses. In this connection it may be noted that most eclipsing binaries are found to have secondaries less dense than their primaries. On the other hand the writer finds, from the data for visual binaries where the necessary information of spectra, parallaxes, orbits and relative masses of the components is known, that, on calculating diameters based on the appropriate surface brightness, the densities of the companions are found to be generally greater than those of the primaries.

It should be mentioned that close binaries may become wider pairs as the result of tidal interaction, but not to so great an extent from that cause as to convert the separations which would result from a process of fission into the distances found in visual pairs. Perhaps mutual perturbations and tidal reactions may be able to assist in this, in the case of multiple systems which are the eventual result of a binary pair first formed by method 2, followed by division of one or both of the pair by method 3. Tidal or other separative force may also help to account for the observed increase of average eccentricity of orbit with length of period, but the chief cause here is perhaps the effect of approaches of passing stars. These tend to make orbits more eccentric, and pairs of longer period, being also on the average most widely separated, are more likely to be "knocked about" by chance approaches.

It must be clear to the reader that there is as yet no satisfactory theory for the origin of binary or multiple systems. It may be that some theory of a catastrophic nature will prove to be the correct one. For instance, E. A. Milne has proposed a nova theory, according to which there is a certain stage in the evolution of a star at which internal instability sets in, resulting in a "collapsed" dense state accompanied by the liberation of much gravitational energy. This, in the case of a rotating star, might be followed by division into two or more components which would not necessarily remain collapsed, with consequent birth of a binary or multiple system. Although this idea involves a stellar model of great central condensation, different from that generally favoured, some catastrophic theory of the kind may perhaps be found applicable even with a model of the gaseous description. Something of the sort seems required to explain the existence of binary pairs like Sirius, composed of a normal star and a white dwarf.

REFERENCES—PART II—CHAPTER III

Same as for Part II—Chapter II, also.

Author.	*Publication.*	*Subject.*
G. P. Kuiper,	*Pub. Ast. Soc. Pac.*, **47,** 121.	"Problems of Double Star Astronomy."
E. A. Milne,	*Observatory*, **54,** 142.	"Dense Stars."
R. A. Lyttleton & F. Hoyle.	*Observatory*, **63,** 40.	"The Evolution of the Stars."

CHAPTER IV

THE CAUSES OF STELLAR VARIABILITY

WE are not yet in a position to state that the causes of light variation in a star are certainly known, except for the eclipsing variables which are not really variable in a physical sense at all. As Russell has remarked, it is probable that if we understood the physical causes of light variation in the stars we should have advanced a long way towards the solution of the problem of stellar evolution.

A successful investigation of the question involves a study of all the data on the subject that can be collected. Meantime, it may be noted that work with the photo-electric photometer by Stebbins and others has made it appear likely that a sensible proportion of all the stars are slightly variable.*

A connection between luminosity and variability, and also between redness and instability of light has been shown to exist by Huffer from studies of 104 red giant stars by means of the photo-electric photometer.

His results were as given below :—

Table 19

Absolute Magnitude.	*Percentage Variable.*
− 4·3 to − 1·2	100
− 1·1 „ − 0·5	45
− 0·4 „ − 0·2	41
− 0·1 „ + 0·1	24
+ 0·2 „ + 0·7	0

Spectrum.	*Percentage Variable.*
M 0	7
M 1	0
M 2	24
M 3	30
M 4	64
M 5	100
M 6	67

* An enquiry made by Mrs. H. Shapley in 1915 led her to conclude that about 3 per cent. of the stars visible to the naked eye were known to vary.

This inconsistency of light in giant diffuse stars suggests an unstable physical condition for the most luminous and reddest and the idea finds support in the observed quasi-periodical variability of the diameters of Betelgeuse and Antares. In the latter, a diameter of 0″·026 has been observed at Mt. Wilson with the interferometer, as well as the 0″·040 given in Table 1.

Stars of the main sequence are believed to be constant in light over ordinary periods of time. It is interesting to note, however, that in 1934, Sir G. C. Simpson (then Director of the Meteorological Office) advanced a theory, to account for the Earth's Ice Ages, that the Sun (a main sequence G type star) is variable with a range of about $0^m{\cdot}4$ in a period of the order of 100,000 years, and that it is now at about minimum.

With regard to the possibility of any secular change in the light of the stars generally, a statistical investigation has been made by Lundmark of the magnitudes of more than a thousand stars in the Star Catalogues of Ptolemy (second century), Al Sufi (tenth century) and Tycho Brahe (sixteenth century). Comparing the values with modern photometric magnitudes and also grouping the stars accordint to modern colour indices he has reached the conclusion that there has been no significant change in brightness or in relative colours* in the period covered, or in the colour sense of the human eye as has sometimes been suggested. He also concludes that the reported increases or diminutions in brightness of certain stars are all due to errors in the earlier estimates. It may be observed, however, that the mean systematic error of these old naked eye estimates as compared with the Harvard photometry values is less than a fifth of a stellar magnitude.

A general survey of the statistics of periodic variables shows three well-defined maxima in the numbers, grouped about the following periods—a half-day, a week (not so marked), and 300 days. The first two are generally classified together as the short-period variables and the third group as the Long-Period stars.

The short-period variables are the "cluster" and "Cepheid" types, although the latter name is sometimes used to include both. The characteristics of their light curves and also the changes in their radial velocities and spectra have been described in the section on Variable Stars. The relation between their periods and luminosities, and their distribution with reference to the Galaxy, have also been referred to.

The causes of Cepheid variation have been the subject of much investigation. The simultaneous changes of brightness, spectrum

* The red colour attributed to Sirius by some classical writers was probably due to the fact that in Mediterranean regions, selective atmospheric absorption makes it red at rising and setting and reddish for some time after rising or before setting.

and colour make it appear that the physical cause is concerned with variation in effective temperature of the surface, however effected. The usual shape of the light curve indicates that rotation of a star with parts of its surface brighter than others cannot be involved, and also shows that eclipses of one component by another are not the explanation. All binary theories seem effectually ruled out. First, because no spectral lines of a secondary have ever even been suspected, and second, because consideration of the probable dimensions of the systems shows that the stars themselves must be larger than the orbits in which the components would move.

The greatness and rapidity of the light changes seem to indicate a periodical transformation of heat energy to some other form of energy and back again, little being lost by radiation in the comparatively small time interval concerned. The form of energy suggested is gravitational energy, and the theory developed in this connection is that of pulsation in the star, whereby a periodical expansion and contraction takes place under the opposing forces of gravitation and gaseous elasticity. The period of such a pulsation should be inversely proportional to the square root of the density (see Appendix K) and it should also depend on the law according to which the pressure of the gas gets greater when the volume is diminished.

The Pulsation Theory.

There has been remarkable progress in development of a theory explanatory of stellar variation (Cepheid and Long Period) as due to pulsation.

In Cepheids, differences in radial velocities between the lines produced by high and low levels of the star's atmosphere are found. The main effect is a lag in the phase of pulsation of the higher levels behind that of the lower ones. The explanation proposed (first advanced by M. Schwarzschild) is that there is a periodic wave of compression of the star's material moving up from below the photosphere into the higher atmospheric regions.

In the case of a Cepheid of short period (less than a day or two) the maximum velocity of approach shown by the displacement of the lines of the spectrum is at or near light maximum. In stars of longer periods this velocity of approach comes after the light maximum at a progressively later phase, until in a Cepheid of long period the star is at its brightest when the velocity curve indicates that it is smallest, agreeing roughly with the original pulsation theory. But in the case of the Long Period variable where the velocity maximum occurs at light minimum, the star appears to be hottest at too early a stage.

The difficulty of the original pulsation theory, as accounting for the phenomenon of Cepheid variation, was that the star was taken to be expanding and contracting with all its parts moving outwards and inwards at the same time. The theory of Schwarzschild altered this by introducing the idea of an outer region of the star in which moving waves of compression progressed outwards to the surface. The central body of the star pulsates as one body, but there are compressional waves in the outer parts passing outwards to the photosphere and from there into the star's atmosphere.

What is observed in light variation and radial velocity therefore depends on the phase the wave is in at the radiating surface, *i.e.*, at the photosphere. The maximum compression occurs at the time of greatest speed of approach to the observer, that is, at the moment of the greatest temperature and light maximum. For the Cepheid with a steeply rising light curve, the maximum and minimum of light both come when the star is decidedly smaller than its mean size, and the total light variation is due to change of temperature and of surface brightness only. The alterations in diameter modify the shape of the light curve.

The increase in the delay between maximum velocity of approach and light maximum with length of periods is explained as follows :—

The longer the period is the larger the star and the more extensive its atmosphere both absolutely and relatively to the size of the star. From this it follows that the time taken by the wave in moving through the atmosphere is not only longer but also is a greater fraction of star's period of variation. There should be a photospheric velocity curve with maximum speed of approach towards the earth (*i.e.*, maximum speed outwards from the star) coinciding with maximum light, this being at the moment the compressional wave reaches the photosphere. But if the level of effective absorption is far above the photosphere, because of extensive atmosphere, then there will be a lag in the velocity curve. In the Cepheids of a few days' period the layer which absorbs is probably close to the photosphere, but with greater periods the absorption takes place at greater and greater heights, and the maximum speed of approach to us occurs at progressively later stages relatively to the time of maximum light. The extreme case in a pulsating variable is for the Long Period class, where the delay is at its greatest.

Formerly it has been thought that the absorption lines in a star's spectrum are produced close to the photosphere ; but this is evidently not always so, at least for a pulsating star ; and it is now considered that in the case of a Long Period variable star the velocity curve from the bright emission lines is what has to be used in considerations of the theory of pulsation.* In fact, if the information for temperature and bolometric magnitude is used to compute the star's diameter and its curve of light variation, and this is compared with a similar curve based on the absorption line velocities, it is found that there is no correspondence in phase. On the other hand, if the velocity curve of the emission lines is taken, the phases are found to agree with those of the calculated curve.

This revised pulsation theory, therefore, appears to give at least a good foundation for explanation of the observed phenomena, both for Cepheids and for Long Period variable stars. The question as to whence comes the energy to maintain the pulsations has not yet received a satisfactory answer, although variations in connection with the production of stellar energy, referred to in a section of the chapter on the subject, seem at least worthy of consideration (see page 86).

Long Period Variables.

As stated earlier, these stars appear to be pulsating giants of large diameter and low density and surface temperature, with visual magnitudes at maximum ranging from about $+0{\cdot}5$ to $-2{\cdot}5$.

Estimates from the spectra give surface temperatures of about 1800° to 2300°. Owing to the great effect on visible radiation of change of temperature at this low range, the change in light (an average of about five magnitudes) is very much greater than the alteration to total radiation or bolometric magnitude ; this is about one magnitude only. The meaning is that the Long Period variable stars really alter very much less in their total output of energy than they do in radiation of the wave lengths that can be photographed or are effective visually. The observed discrepancy is partly due, however, to excessive absorption by titanium oxide bands at minimum light. It is thought that it may possibly also be partly a consequence of the formation of cloudy veils of liquid or solid particles condensing from the star's upper atmosphere ; such a phenomenon might provide an explanation of the irregularities in the amplitude of light variation as well.

Irregular Variable Stars.

Of the known irregular variable stars, all but those connected with the Orion nebula and the T Tauri type seem to be giants of

* The original level of the bright line emission appears to be below that of the absorbing (reversing) layer which produces the dark lines of the spectrum, suggesting that "at a certain phase in the light cycle, masses of superluminous gas may appear in or near the photosphere and, as the cycle advances, rise through the reversing layer until they disappear at an upper level." (Merrill, *Pub. Ast. Soc. Pacific*, 1946, October, p. 305).

large size and small density. The suggestion sometimes made that the variation is caused by opaque interstellar clouds drifting between us and the star may be the correct explanation for the faint Orion variables, which seem to be probably, but not certainly, dwarf stars—they may be heavily obscured giants in or near the nebula, or lightly obscured giants at a greater distance beyond. The same hypothesis is not so suitable for the giant irregular variables however, as there are spectral changes in these stars which suggest some intrinsic cause. For instance, R Coronae Borealis, which remains for years at about the sixth magnitude and rapidly drops several magnitudes occasionally for an interval that may be short, or may be several years, has a spectrum of G0 type when at its brightest, but shows enhanced metallic lines at minimum. Recently, it has been suggested that the drop in its light is caused by clouds of condensed carbon vapour in its atmosphere.

SS Cygni also has a variable spectrum with wide dark bands due to hydrogen at maximum, but a bright O type spectrum at minimum. The variation of α Orionis appears to be connected with pulsatory changes in its diameter, as shown by interferometer measurements at Mt. Wilson. The Veil theory of formation of obscuring clouds in the star's atmosphere has been suggested for giant red irregular types; also that spots of the solar kind, but on a gigantic scale, are responsible for the variation in light.

Novae.

The great suddenness and the enormous increase of light characteristic of a Nova or Temporary Star, when considered in conjunction with the spectra, seem to show that an explosive outburst is concerned. For example, the increase in light output for five conspicuous Novae of the twentieth century ranged from 11 to 13½ magnitudes with a mean of 12½ magnitudes, corresponding to a hundred-thousand-fold change.

Several explanations have been put forward. These may be divided into two types according as they account for the explosion as due to outside influences or to causes chiefly intrinsic in the star itself. The simultaneous presence of the bright line and absorption spectra led to the idea of two stars colliding, or passing very close to one another with resulting violent outbursts due to tidal disturbances. This theory would account for the suddenness of the phenomenon and also for the more gradual fading in the light. In one form it would involve the hypothesis of one star with an absorption spectrum moving towards us with great velocity and another star with a bright line spectrum moving from the Earth at a small speed. This coincidence seems an extremely unlikely one and moreover the frequency of appearance appears to be much too great when the enormous distances between the stars, even in Milky Way regions where Novae are most frequent, is considered. (See Appendix H).

Another objection is to be found in their return in the course of a few years to their former level of brightness, a most unlikely occurrence to any bodies concerned in a violent collision at stellar velocities.

Practically all theorists have therefore of late favoured an explanation of the phenomena of Novae as due to a sudden development, or release, of sub-atomic energy somewhere beneath a star's surface, causing violent expansion at speeds beyond gravitational control. The star's surface layers swell but keep on radiating like any other stellar surface, and they give a continuous spectrum. This enlargement of radiating surface causes a very great increase of the star's apparent brightness; but later on the expanding shell becomes thinner and transparent, and is then excited to shine more strongly by the very short wave high energy radiations from the inner regions of the central star, exposed by the loss of its lower temperature surface material. The result much exceeds the light of the star itself, which rapidly decreases, the bright lines or bands from the moving envelope being very strong while the continuous spectrum from the star is practically unobservable. As the expanding shell thins out and dissipates in space, the bright lines fade and disappear, leaving the continuous stellar spectrum of the star at its eventual brightness. The spectral phenomena described in an earlier chapter are in the main due to the moving shell; this produces absorption lines, displaced towards the violet where it comes between the star and the observer, and bright broad lines or bands from the other parts which have motions in all directions with respect to the observer, varying from zero to large velocities of approach and recession. It is suggested that there may be a zone of instability under the surface of such stars as "explode" into Novae. The slightest disturbance to a zone of the kind, either from inside or outside of the star, would upset the state of convective or radiative equilibrium of the star's interior and cause a sudden outburst of radiation.

The idea has been advanced by McLaughlin and others that Novae may be the result of repeated outbursts of a star. Several Nova-like stars (*e.g.*, T Coronae Borealis) are known which repeat* the interval between the great increase in brightness being pro-

* The list of recurrent novae now includes T Coronae Borealis (1866, 1946), R S Ophiuchi (1898, 1933), T Pyxidis (1890, 1902, 1920, 1945), Nova Sagittae (1913, 1946), Nova Sagittarii (1901, 1919), and U Scorpii (1863, 1906, 1936). These six stars are possibly a group connecting the SS Cygni and U Geminorum type variables with normal novae.

portional to the range of light change, and it is thought possible that those of much greater range may really repeat at intervals of several thousand years. If the phenomenon is not a recurring one, to a particular kind of star, then it appears likely that most, if not all, stars pass through a Nova stage, judging by the number which appear and by the age of the stellar system.

The great gap between the luminosity of an ordinary Nova and that of a Supernova, and the much greater radial velocities of emission of the latter, have suggested that the causes are of a different nature. The possibility that a collision of two stars may be responsible for the Supernova has been discussed. Although their frequency is of the order of a ten-thousandth that of a normal Nova, it would seem (see Appendix H) that their frequency, if due to collision, would be much less than every 600 years for an average galaxy as estimated by Zwicky, or that suggested by the 1054, 1572 and 1604 Galactic Supernovae.

REFERENCES—PART II—CHAPTER IV

Author.	*Publication.*	*Subject.*
A. S. Eddington,	"The Internal Constitution of the Stars."	General.
A. S. Eddington,	"Stars and Atoms"	General.
Russell, Dugan and Stewart.	Young's "Astronomy."	General.
L. Campbell and L. Jacchia.	"The Story of Variable Stars."	Variables and Novae.
C. & S. Gaposchkin,	"Variable Stars."	Do.
P. W. Merrill,	"The Nature of Variable Stars."	Do.
D. B. McLaughlin,	*Popular Astronomy,* **49**, 292, 457.	Novae and Supernovae.
F. Zwicky,	*Astrophysical Journal,* **88**, 529.	Frequency of Supernovae.

Part III—The Stellar Universe

CHAPTER I

THE GALACTIC SYSTEM

EVEN a cursory naked eye examination of the sky shows a very evident tendency to grouping amongst the stars. Such asterisms as Ursa Major, Orion and Scorpio, although loose aggregations, seem closer together than random distribution would produce; and there is a gradation from these through clusters like the Coma Berenices stars, the Hyades, the Pleiades, Praesepe, on to those clusters which are revealed only by telescopic search. Of greater structural importance may be many large and bright patches in the Milky Way regions of the sky often several degrees in extent, which a good telescope or a photograph of long exposure shows to be composed of myriads of faint stars. On the other hand, their outlines are perhaps often largely due to the effect of the obscuring clouds found throughout galactic regions. The star clouds in Sagittarius, Cygnus, Scutum, Argus and Auriga are the most prominent of these bright aggregations.

As regards the physical connection of the stars in asterisms or clusters, such as are referred to above, it is of interest to note that in 1767 the Rev. John Michell showed that the probability against their being chance dispositions is very great. For example, he found in the case of the six brightest Pleiades, that the odds are half a million to one that, out of the 1500 naked-eye stars as bright as or brighter than they are, no six stars would be found within the area of the sky occupied by them.

The Milky Way or Galaxy is in appearance a luminous belt of stars of irregular outline and width, the centre line of which is approximately a great circle of the sky. This centre line passes the celestial North Pole at a distance of about 30°, and runs through Cassiopeia, Perseus, Auriga, Monoceros, Argo, Crux, Centaurus, Scorpio, Sagittarius, Aquila, Cygnus and other constellations. It is divided into two streams for about a third of its length by an irregular dark band, the brighter of the streams passing through Scorpio and Sagittarius and joining the other at Cygnus. Its width varies considerably, from about 10° to 40°, and the brightness is also different from one point to another. It is at its brightest in the star clouds of Sagittarius, but is also prominent in other regions such as Aquila, Cygnus and Centaurus. In the areas of average brightness, such as those in Cassiopeia, Perseus or Monoceros, its light is equivalent to that received from about four to five stars of the sixth magnitude per square degree.

Readers may be interested in the results of the work of the Belgian nineteenth-century astronomer Houzeau. Observing in Jamaica, he made careful drawing of the Milky Way and estimates of its brightness to the naked eye. Of the seven brightest regions only one (4° east of α Cygni) is north of the celestial equator. The seven are as follows, roughly in order of brightness: 7° west of ϵ Sagittarii; 3° north of μ Sagittarii; 2° north of γ Sagittarii; 3° east of α Scutum; 6° south of α Scutum; 6° west of ζ Arae; 4° east of α Cygni. It will be noted that the three brightest are near the galactic centre in Sagittarius. Houzeau also recorded a number of regions somewhat less luminous than these seven. In this next grade of brightness there were twelve, and of these the following seven are in the northern celestial hemisphere; 3° north of β Cassiopeia; midway between δ Cassiopeiae and γ Persei; 3° west of η Geminorum; 3° east north east of β Cygni; 5° south west of γ Cygni; 9° east north east of α Cygni and 4° north west of γ Aquilae. All these positions are in or near the brightest Milky Way regions, as shown in modern small-scale photographs.

According to van Rhijn's measures the luminosity of the Milky Way zone is not very much greater than that of the other parts of the sky, being less than twice as luminous on the average; but if that part of the general illumination of the sky*, due to permanent aurora and zodiacal light, could be eliminated, the ratio of average galactic to non-galactic brightness would be several times increased.

The observed centre line of the Milky Way is not a great circle, but is about 1° south of the great circle which is taken as the galactic equator. The galactic poles are in R.A. $12^h 47^m$ Declination + 27°, and R.A. $0^h 47^m$ Declination − 27°, the former in Coma Berenices, the latter in Sculptor. Galactic latitudes are measured from the great circle of which these are the poles, and longitudes are measured eastward from the point of intersection or ascending node of the galactic equator on the celestial equator at R.A. $18^h 40^m$, situated in the constellation Aquila. Such co-ordinates are of great importance in investigations of the structure of the universe, as the galactic plane is evidently the fundamental plane of reference for our stellar system, corresponding to the ecliptic in the solar system.

* The total general illumination of the night sky is caused by diffused Aurotal and Zodiacal light plus stellar light and a faint background of starlight reflected from interstellar matter. It is estimated to be about equal to that produced on a surface by a candle, distant 185 feet, *i.e.*, by a star about three times as bright as Venus at its brightest.

In Part I, Chapter II, the question of the concentration of stars of different types with reference to the Galaxy has been dealt with, from the point of view of galactic latitude and longitude, in Tables 8 and 12 respectively, and on pages 34, 35. The concentration in latitude has long been recognised as suggesting a grouping in space in the form of a flattened disc.

The Galactic Nebulae.

Leaving aside for the time being the consideration of the structure of the galactic system, it is desirable to consider the various forms of nebulae and clusters which are known to be scattered throughout the system of the Milky Way. It was formerly frequently remarked that there seems to be a clear distinction between nebulae situated in Milky Way regions and those elsewhere in the sky. This was hinted at by the classifications of the Herschels and is now accepted by all astronomers. The galactic nebulae, comprising only a small percentage of the many thousands of nebulous objects known, are divisible into principal types as follows:—

1. Planetary.
2. Diffuse:
   - (*a*) Luminous.
   - (*b*) Dark.

Of the planetary nebulae, there are about a hundred and fifty known. Their appearance is as round or oval masses of faint nebulosity, very often with a central star and with a considerable amount of detail, sometimes consisting of concentric shells of light occasionally showing as a ring formation, which has a star in the centre and is not completely dark.

R. H. Stoy has proposed a classification into six groups: α, irregular, with several bright condensations and with or without faint outlying nebulosity; β, a bright ring or sometimes two rings, the outer broken and fainter, superposed on a fainter disc with a more or less conspicuous centre star; , small and disc-like, with uniform brightness or brighter towards the centre, the central stars when visible being faint; δ, stellar in appearance, but known from spectra to be planetaries; ϵ, three specimens known from their spectra as the "hydrogen nebulae," with conspicuous central stars; θ, relatively large and with low surface brightness, but conspicuous central stars. He thinks that judging by apparent galactic concentration, group θ are nearest, next are group γ, and furthest away, group δ.

The sizes of the planetaries range from a few seconds up to 12′ in diameter, but most of them are less than about 1′ across. The central stars are generally fainter than tenth magnitude photographically, and being evidently very hot and bluish in colour are still fainter visually. The fact that the apparent diameters are smallest in general for those nearest the Galaxy suggests that they may be roughly of the same order of size, the more remote ones having low galactic latitudes as a consequence of their distance. On this assumption, statistical investigation, using apparent angular diameters together with proper motions, has provided an idea of distances. These appear to range from about 1500 light years to as much as 50,000 light years, mostly lying between 3000 and 30,000 light years. For the most part inside a stratum 10,000 light years thick, the centre of which is approximately the galactic plane, they are, as is shown earlier on Table 12, noticeably concentrated towards the centre of the Milky Way system in Sagittarius. The following table gives distances and dimensions of a number of these objects, derived as above described, and therefore not likely to be more than approximate.

Table 20

Designation.	*Distance* (*light years*).	*Radius* (*astronomical units*).*	*Temperature.*
NGC 1535	5600	15,500	10,000° K
NGC 6543	3500	10,800	6,000°
NGC 6572	4000	8,600	9,200°
NGC 6826	3400	13,600	7,200°
NGC 7009	3000	8,400	9,500°
NGC 7027	7000	10,600	9,500°
NGC 7662	3900	10,000	10,300°
IC 418	5900	10,800	6,800°

(* Astronomical unit = radius of Earth's Orbit).

The fourth column gives the temperatures of the nebulae themselves derived from their spectra. The ultra-violet radiation of the central stars, after absorption by the atoms of the nebulae, causes the observed emission of light from the nebular material. The photographic magnitudes of the nebulae range from about the same as those of the central stars to as much as six or seven magnitudes brighter; the greater brightnesses are observed in the case of the nebulae containing the hottest of these central stars, whose temperatures range from about 25,000° to over 100,000°. Rotational velocities have been measured spectrographically, the lines being inclined when the slit of the spectroscope is placed along the major axes of the figures of the nebulae. From these velocities and assuming appropriate distances and dimensions, masses equal to a fraction of that of the Sun have been derived. With diameters

of about 20,000 to 30,000 times the distance between the earth and the Sun, planetaries are therefore what might be termed "glowing vacua," thousands of times more tenuous than the best vacuum obtainable in our laboratories.

The chemical composition of the planetary nebulae does not differ essentially from that of a star like our Sun. Hydrogen, oxygen, nitrogen and neon are abundant according to the spectra, and small proportions of the metals are also part of their composition. The luminosity is produced by a process similar to fluorescence. The total amount of photographic light radiated ranges from as much as, to more than, 100 times that of the central stars, whose high temperature means energy emitted as invisible ultra-violet radiation. This is absorbed and re-radiated by the nebular atoms, in longer wave-lengths, which can be photographed or seen. The hydrogen atom is the chief agent concerned in this transformation.

As regards the origin and evolution of the planetary nebulae, the suggestion that they are the relics of Novae has already been considered but not favoured (see page 58). A Nova perhaps always passes through a quasi-planetary-nebula stage, but that stage does not last. In normal planetaries the radial velocity movements, as measured by the spectroscope, are of the order of 10 miles per second as against fifty or more times as much in the case of Novae; it appears likely that they are the products of stars that reach a state in which the energy generated is too much for the retention of their outer layers, and the star blows off large amounts of matter until it again reaches a state of equilibrium. Such a star would appear surrounded by a luminous shell that would increase in size, starting as a nebula of a bright condensed type and becoming one of a more diffuse appearance with a bright ring or rings seen on a fainter nebulous background. This line of evolution was suggested by R. H. Stoy and appears to have much to commend it. It must be remembered, however, that the two Supernovae of our Galaxy, which appeared in 1054 and 1604, are believed to have left masses of nebulosity in their places, one of which (the Crab Nebula), connected with the 1054 star, has been classified (perhaps wrongly) as a planetary nebula. Is it possibly the case that this happens with a Supernova, although with an ordinary Nova the ejected nebulosity thins out and practically disappears?

The diffuse nebulae are irregular in shape and they range from small wisps and streaks, only observable by means of long exposure photographs, to such objects as the Orion nebula easily visible without optical assistance. As in the planetaries, in most cases diffuse nebulae are associated with stars in such a way as to suggest that there is some relationship.

In 1912, V. M. Slipher of the Lowell Observatory, Flagstaff, Arizona, discovered that some of the diffuse nebulae have dark line spectra ; the Pleiades nebula round Merope, for instance, has a spectrum similar to the one shown by that star (23 Tauri, $4^{m}\cdot2$, B5 type). He suggested that the nebulae in this cluster shine by light reflected from its stars, and photometric measures by Hertzsprung in 1913 gave support to the idea. This led to a new view of the source of light of the gaseous nebulae. Later work by Hubble at Mt. Wilson gave the following results for planetary and diffuse nebulae :—

Table 21

Type.	*Appearance.*	*Associated Stars.*	*Remarks.*
Small planetaries.	Less than 2′ diam.	Bright line O type.	Nebulae absorb
Large planetaries.	Over 2′ dia.	Between bright line O and Oe5.	and re-emit
Diffuse with bright line spectra.	Usually wispy.	Oe5 and B0.	radiation.
Diffuse with continuous spectra.	Usually smooth and cloudy.	B1 and later.	Nebulae reflect radiation.

Hubble has remarked that, since nebulae with bright line spectra are more easily identified for a given surface brightness because of the concentration of their light in the discontinuities of their spectra, they are actually the less numerous, although about equal numbers of bright line nebulae and nebulae with continuous spectra are known. A detailed discussion showed that, with the exception of about four objects, each nebula had associated with it one or more stars of a type as given in the above table. This suggested that the source of luminosity of the nebula is the radiation from these stars, the nebulosity consisting of clouds of matter, molecules, dust or perhaps larger particles not hot enough to be self-luminous, but visible because of light excited by or reflected from the involved or neighbouring stars. Adopting this hypothesis, Hubble has related the brightness and angular extents of the nebulosities to the photographic magnitudes of the stars. Assuming that the intensity of illumination varies inversely as the square of the distance from the stars, and that the nebulae absorb and re-emit, or reflect, the radiation falling upon them, he showed that, theoretically, for a constant ratio of focal length to aperture and with 60 minute exposures, $m + 5 \log a = 11\cdot6$ or $10\cdot6$, according as the line joining the star to the nebulosity is perpendicular to it or has the mean inclination

corresponding to random direction (m being photographic magnitude of the star and a the maximum apparent angular extension of the nebulosity from the star). When the values of m and $\log a$ for 82 diffuse nebulae are plotted, the points lie along a mean line, falling between the two lines derived from the above formula, thus proving the substantial correctness of the assumptions. In thirteen cases the value a is greater than the maximum possible on this theory for the magnitudes of the stars concerned, but a satisfactory explanation seems to be that the stars are partially obscured by nebulosity intervening between them and us, the excess of colour for the spectral types being abnormally great in these cases. Hubble also showed that for exposures of 160 minutes, with reflectors of focal ratio 1 to 5, nebulosity would be photographed which is situated at the following distances from stars of the photographic absolute magnitudes given :—

M.	*Distance in Light Years.*
× 5	32
0	3
+ 5	0·3
+ 10	0·03

The nebulosity in the Pleiades shines by reflection of light from the enclosed stars. In the case of nebulae with continuous spectra, their colours have been found to be nearly the same as those of the stars concerned, an outstanding example being the large reflection nebula near the red supergiant Antares. This nebula is about a degree in angular breadth and is several light years in diameter.

The dimensions of the diffuse nebulae are often very great. For instance, the Orion nebula, which is also nearly a degree in diameter, and is approximately 980 light years away, is more than 14 light years across, while one nebula in the large Magellanic Cloud must be (adopting Shapley's estimate of distance) several hundred light years in diameter or sufficiently large if placed at the distance of the stars in Orion more than to fill that constellation !

If stars or clusters are involved, distances and dimensions are derivable. Trumpler has found the following values for several well-known diffuse nebulae, all connected with galactic clusters :—

	Distance (light years)	*Diameter (light years)*
Pleiades nebula ...	500	50
"Trifid" nebula (M20)	3200	20
"Lagoon" nebula (M8)	3600	36 by 55
N G C 2237	4400	75
M16	6700	40

The spectra of gaseous nebulae were found to be fairly similar to one another, all the lines being sharp, as would be expected from a gas of low density. The bright lines observed were of hydrogen, helium, and (occasionally) singly ionised carbon and doubly-ionised nitrogen, but the most conspicuous lines were those of a hypothetical substance "nebulium," at wave lengths λ 5007 and λ 4959; which were referred to as the N_1 and N_2 lines. There are a number of other lines also and all of them vary in relative strength from one type of gaseous nebula to another.

For some time it seemed to be certain that these lines are not produced by a hitherto undiscovered element or elements, but by the radiations of ionised atoms of known elements subject to physical conditions not produceable in terrestrial laboratories. The spectra of the light elements, which are thought to form the chief constituents of nebulae, are well known and it was therefore considered probable that some cause, such as a density much lower than can be produced terrestrially, must be the reason for the unidentified radiations. From considerations of physical theory based on laboratory experiment, Bowen has shown that the extremely low densities prevalent in nebular matter and the consequent long intervals between atomic collisions, provide the conditions for radiations of the wave lengths concerned, from atoms which have lost one or more electrons. When gases are at ordinary pressures, or even at the low pressure of a so-called vacuum tube, the atoms collide very frequently, and change the energy they contain at each collision. In the course of these changes they pass occasionally through states known as "metastable" conditions, in which they have given out nearly all their energy, and do not radiate light under ordinary circumstances. But at the extraordinarily low densities of the nebulae, a cubic mile probably containing less gas than a cubic inch of our air at sea level, collisions are extremely infrequent, (Bowen estimates the mean interval as from 3 hours to 5 days) and the metastable atoms get an opportunity to radiate before their condition is altered by a collision. It has been found, for example, that the following nebular lines are thus due to oxygen: a red line at λ 7325, the green "nebulium" lines at λ 5007 and λ 4959, the blue line at λ 4363, the ultra-violet one at λ 3727 and possibly others in that region, while those in the violet at λ 3868 and λ 3967 are similarly produced by neon.

It is noteworthy that the explanation has been arrived at through theory based on laboratory experiment, but not by actual production of the spectral lines in question in a terrestrial laboratory.

Several nebulae are known to vary in shape and brightness. Two of the most remarkable are NGC 6729 in Corona Australis and NGC 2261 in Monoceros. They both resemble a comet in shape and each has a nucleus at the head, consisting respectively of the irregularly variable stars R Coronae Australis and R Monocerotis. The spectra of both these nebulae are continuous, with faint bright lines superposed, and are somewhat similar to those of the nuclei. Changes in the nebulosity take place with great rapidity, details disappearing and reappearing as if subject to obscuration by moving masses. NGC 6729 is in a region in which obscuring clouds have been observed, and its distance has been estimated by Hubble to be about 300 light years. As already stated, the luminosity of diffuse emission nebulae is due to excitation of the atoms of gas by radiation, but it should be borne in mind that it does not follow that these nebulae are entirely gaseous in constitution. It may be that only the gaseous portion can shine under the influence of the radiation, and there is almost certainly also a considerable quantity of dust and solid matter.

As regards the temperature of a diffuse gaseous nebula, if this is measured in terms of atomic and molecular motion, it may be said that at about a light year from the exciting star, the nebula, however tenuous, has a temperature of thousands of degrees. The temperature of interstellar space itself can be otherwise defined, however. If measured by the equilibrium temperature of a small meteoritic particle more than a light year or so from any star, it is probably only two or three degrees above absolute zero (2° or 3°K).

The line-of-sight velocities of diffuse nebulae with respect to the Sun, as measured from their bright line spectra, are found to be in general relatively small, *e.g.*, Orion nebula (M42), zero; η Argus nebula, 3 miles per second approaching; "Trifid" nebula (M20), 14 m.p.s. receding; and M8 and the "Omega" nebula (M17), 5 and 13 m.p.s., both receding, respectively.

Obscuring Clouds in Space.

The existence of "dark nebulae" or obscuring cosmic clouds is, following Barnard's pioneer work, now known to account for most of the dark markings in the Milky Way and for dark starless regions in various parts of the sky. On the Franklin-Adams photographs of the sky Lundmark and Melotte counted 1550 dark areas, covering about 850 square degrees, most of which are probably due to obscuring clouds, mainly in Milky Way areas. In some cases, as in the region of the Pleiades, Orion and Ophiuchus, these dark clouds merge into luminous nebulosity in the neighbourhood of certain stars, showing that they are physically connected. The distances of these stars are known, so that it is believed that the dark clouds of Taurus, Ophiuchus and Orion are situated at about 500, 500 and 650 light years respectively. The dimensions of these dark clouds are very great, as much as 70 light years in length by about a twelfth of that in breadth in the case of the dark lane east of ρ Ophiuchi, while the dark cloud or clouds which produce the bifurcation of the Milky Way from Cygnus to Centaurus (nearly 120° long) is much larger in extent and in Cygnus it is estimated to be at 2000 light years distance. The cloud which produces the "Coal Sack" near the Southern Cross is probably about 300 light years from us.

There is good reason to believe that the obscuration of these clouds is produced chiefly by dust, although other particles of some size may be present. Fine dust, having a much greater surface per unit of mass, is very much more effective in stopping light, and an extremely small amount per unit of volume would be completely opaque. Russell states that even a milligram per square centimetre (less than a tenth of an ounce per square foot) whatever its thickness, would be sufficient, which would mean an aggregate mass of about a dozen times that of the Sun for a dark lane like that in Ophiuchus. The clouds cannot be gaseous as the quantity of matter required would produce dynamic effects, shown as motions of the neighbouring stars, which are not observed. Finely divided meteoric matter would behave in a field of stellar radiation as follows, assuming the particles to be spherical, opaque and practically non-reflecting. Except for light pressure, which is doubled if the particles reflect perfectly, the effects produced are not much altered by changing these properties. If the particles are larger than ten times the wave-length of the light concerned, their power of stopping in stellar magnitudes is very nearly equal to the sum of the cross sections of all the particles in a given cylinder divided by its cross section. With smaller sizes, this ratio has to be multiplied by from 1·0 to 2·5, this factor increasing as the diameter decreases to about a third of the wave-length. For still smaller particles, the factor decreases, however, from 2·5 to nearly zero. Particles with a density of 2·5 times water and a diameter of a twenty-five thousandth of an inch with a mass of about a fifteenth of an ounce per square foot, no matter what the depth of space is, will reduce light by approximately one stellar magnitude. In order to show the very much smaller effect of absorption by gas, it may be here remarked that the earth's atmosphere, which dims starlight at the zenith by less than half a magnitude, has more than half a million times as great a mass as this above each square foot.

As regards the effect of light pressure, since gravitational attraction and repulsion by light pressure both vary inversely as the square of the distance, a particle for which repulsion exceeds gravitational attraction near a star will be repelled from the star at all distances. For particles of a given density there are two values of diameter where there is a balance. Particles between these limits are repelled, those outside the limits are attracted. The limits depend on the luminosity and mass of a star and for a massive star of low luminosity the limits may actually coincide, so that all particles of any size would be attracted.

It has been suggested that the dust clouds may be accumulations of material repelled by the radiation of the stars, but observation of solar prominence phenomena seems to show that most ejected material probably falls back on its surface.

Comparatively Unobscured Regions.

The more obscured regions of the Milky Way have been given considerable attention, several of them being referred to above, such as the chief one of the kind, the great Rift from Cygnus to Centaurus where the dark obscuring clouds are at 2000 light years distance in Cygnus, although in the more southern parts of the Rift dense dark nebulae show their effect 400 or 500 light years away. These distances are obtained by various methods, including one involving counts of stars down to given magnitude when deficiencies in the numbers at particular magnitudes (the average distances of which are known) point to the required distances of the obscuring cloud, while the deficiencies in the numbers for the faintest magnitudes indicate the total obscuration due to the absorbing material. But in certain directions there appears to be a relative transparency, notably towards the Milky Way star clouds in Sagittarius, Cygnus, Cepheus, Auriga, Argus, Scutum and Aquila, where on the average the obscuration does not seem to be more than the general one described in Part I, Chapter II, that is, of the order of less than one magnitude per 3260 light years (1000 parsecs).

Galactic Clusters of Stars.

These are sometimes referred to as "Open" clusters which distinguishes them from the more condensed globular type. More than 300 have been noted as the result of visual and photographic work. They range in apparent size from clusters like the Pleiades or Praesepe, on the one hand, to faint collections made up of a few telescopic stars on the other. The stellar populations vary from hundreds of members in such cluster as the double one in Perseus (see Plate 7b) down to small numbers of stars which can hardly be distinguished from chance groupings ; and the degree of concentration of the stellar contents to a centre varies widely. Distances and dimensions have been estimated chiefly by means of the method of "spectral parallax" (see Appendix D), the spectra of their stars showing generally a well-marked correlation with magnitudes similar to the configuration of Fig. 1. Trumpler has classified them in accordance with the types of stars contained; the following is based on his classification. A typical cluster is given under each heading :—

Table 22

GALACTIC CLUSTERS.

	Clusters with no yellow or red giants.	*Clusters with both giants and dwarfs.*
Clusters with stars hotter than B8 type.	Pleiades.	Cluster round. θ Carinae (Melotte 102).
Clusters with no stars hotter than B8 type.	Messier 34.	Praesepe.
Clusters containing only stars of F0 to M types.	(Not observed through faintness of constituent stars ?)	NGC 752.

Shapley's classification is on the basis of two main characteristics —numbers and concentration of stars, and distribution of spectral types of the contained stars. For the first of these he gives seven groups from (*a*) field irregularities, to (*g*) the richest and most compact type. In practice, however, only (*c*) to (*g*) are used, all of which are compact and increasingly rich and concentrated. The other characteristic involves two principal groups based on spectra or colours of stars, (1) the Pleiades type, with all its stars in the main sequence, (2) the Hyades type, with yellow spectral classes (G, K or M) of the same apparent brightness as the more common A type stars in them.

The spacing of the stars in a galactic cluster must be considerably closer than in the solar neighbourhood* and an observer situated at the centre of one of them would probably see many stars nearer to him than α Centauri is to the Sun, some shining more brilliantly than Sirius does in our skies. Unlike the globular clusters, the galactic type appear to contain very few variable stars, which is probably a fact of some significance in the origin and history of these clusters.

Since Trumpler's demonstration of the amount of absorption of light, referred to in Part I, Chapter II, the distances found have been always by methods which allow for the effect of this obscuration. In addition, study of the colour indices of the stars in star clusters, for which excess of colour due to selective absorption in space can be derived, provides a valuable method for distance estimation, applicable to clusters considerably more distant than those where spectral types of the contained stars can be ascertained.

* One investigator puts the density of stellar distribution as from 5 to 250 times as great for the stars brighter than the limits of the photographs studied by him, the real densities being therefore even greater.

When the distribution of the clusters in space is discussed, it is found that they are grouped round a centre situated near the Sun and show no clear relation to any structural features of the Galaxy. Out to about 6500 light years distance the distribution is more or less uniform, but beyond that distance they appear to thin out quickly, and the limit of distance so far reached is not more than 16,000 light years. Trumpler has shown that this very probably only demonstrates the inadequacy of our data. He gives the effect of the absorbing layer in the vicinity of the galactic plane as the most serious obstacle in the search for more distant galactic clusters, another being the heavy effect of the obscuring Milky Way dark clouds. In addition, however, he has shown that there would be great difficulty in distinguishing any clusters at remote distances, owing to the greatly increased number of faint background stars then photographed, or seen, along with the cluster stars, in greater relative numbers. In fact, he demonstrates that, for example, the Pleiades and Praesepe (each distant about 500 light years) would not be detectable as clusters beyond about 16,000 light years, owing to the effect of background stars, on photographs taken with ordinary plates. On photographs using light of longer wave lengths which is less absorbed by interstellar dust, greater distances could be investigated with the help of instruments of large aperture and wide field. This would help to bring out some structural galactic features so far not detectable by study of galactic clusters.

Another useful application of photography on red-sensitive plates may be found in the added ability to study galactic clusters which may be behind obscuring dust clouds or nebulae. For example, photographs of the kind, taken with Mt. Wilson 100-inch have revealed that the well-known trapezium of stars in the Orion nebula (M 42) is at about the centre of a cluster of 130 fainter stars 5′ in diameter. The four trapezium stars are supergiants of early spectrum, the others are dwarfs of later types. It seems probable that this group is part of a normal galactic cluster blotted out by the nebular obscuration except close to the trapezium.

The distribution in galactic longitude of 334 of these objects is as follows in percentages :—

Longitude 90°-180°	*Longitude* 180°-270°	*Longitude* 270°-360°	*Longitude* 0°-90°
26	29	31	14

The small number in the 0°-90° quadrant is undoubtedly due to the obscuration by the dust clouds of the Milky Way from Aquila to Cygnus (part of the great Rift).

As regards distribution on the sky in galactic latitudes, very few (9 per cent.) are outside 10° north or south; in fact, there are only four listed clusters in higher latitudes than 30° north or south. The concentration to the galactic plane is therefore very pronounced, practically all being inside a layer less than 4000 light years thick.

Distances and dimensions of a selection are :—

Table 23

GALACTIC CLUSTERS.

Cluster.	*Distance* (*light years*)	*Diameter* (*light years*)
NGC 752	1300	17
Perseus double cluster ...	4300	40
M 34	1450	13
Pleiades	500	20
M 38	2800	15
M 36	3200	15
M 37	2700	19
M 35	2700	23
M 41	1300	12
M 50	2700	13
M 46	2100	16
Praesepe	500	13
M 67	2400	13
Group θ Carinae	800	18
M 6	1700	13
M 7	800	12
M 23	2100	16
M 25	3200	33
M 11	4400	16
M 71	4000	10
M 39	1100	11
M 52	4500	17

The diameters above are from "estimated" angular diameters and are of the more central parts of the clusters; "limiting" or overall dimensions based on counts of the cluster stars with allowance for the normal stellar background, would be generally 2 to 3 times as large. There appears to be a systematic connection of diameters with stellar concentration, and also with poorness or richness; the diameters are less with greater concentration but increase with richness. Nearly half are from ten to fifteen light years in diameter, and three-fourths from about seven to twenty light years ("estimated" dimensions); the overall figures are about fifteen to sixty light years, for all physical types of cluster, the majority being between thirty and fifty light years.

IS THERE A "LOCAL" SYSTEM?

The late Dr. B. A. Gould was of the opinion that a belt or stream of bright stars girdles the sky nearly in a great circle forming an angle with the Milky Way, the northern point of the intersection being in Cassiopeia and the Southern near the Southern Cross. Sir John Herschel had previously thought he recognised the southern part of such a stream and believed that the appearance of the bright stars gave reason "to suspect that our nearest neighbours in the sidereal system form part of a subordinate sheet or stratum deviating . . . . from parallelism to the general mass which forms the Milky Way." By means of studies of distribution of the B type stars brighter than $7^{m}{\cdot}0$, Shapley showed that their mean line of position seemed to be inclined at about 12° or 14° to the galaxy and that it coincided approximately with Gould's belt of stars, although the fainter and more distant stars are more closely confined to the galactic plane itself. From the relatively uniform absolute magnitudes of B stars it was possible to ascertain their distribution in space and find that they appeared to form a flattened cluster with its equatorial plane inclined to the plane of the Milky Way. The work of Charlier was considered to confirm the existence of the cluster, the dimensions of which were about 3000 light years diameter by about 800 light years thickness, the centre lying in the direction of the constellation Argo (galactic longitude 240°) at 300 light years distance from the Sun. Another type of stars found to be concentrated towards this part of the sky are M stars brighter than $8^{m}{\cdot}0$ (see Table 12). A considerable fraction of the brighter A stars appears to belong to this "local system," and it has been thought that the galactic bright and dark nebulae are concentrated in it and in the much farther off Milky Way star clouds, the regions between being apparently practically devoid of such objects.

Recent work has, however, produced results which do not all favour the actual existence of this Local Cluster. This work is based on counts of stars with different assumed values for space light absorption. Bok (using an absorption of 0·4 magnitude per 3260 light years, or 1000 parsecs) found a result in favour and others have obtained similar results. But Oort, using different methods, in which counts of numbers of the nebulae outside of the galactic system visible at different galactic latitudes were employed as a means of estimating the loss of light of the stars due to absorption, arrived at the view that the Sun's neighbourhood is one of low, and not high, density of stellar population, suggesting that we are situated in a "local void" in the Milky Way system, perhaps between arms of a galactic spiral nebula.* Some astronomers consider, therefore, that the conception of a clearly marked Local Cluster will have to be abandoned; but it is difficult to see how the distribution in galactic longitude and in distance outwards of such objects as the bright B and M type stars, can otherwise be explained. It may be noted that the different speeds of rotation of the stars round the centre of the galaxy, decreasing from that centre, would seem to entail that the existence of such a Cluster could only be temporary. On the other hand, there are condensations on the arms of spiral nebulae which may be such local clusters in the systems concerned.

The Globular Clusters.

Of these beautiful objects about 90 are listed, ranging from that known as 47 Toucani, which is nearly 1° in diameter as measured by densitometer on photographs and visible to the naked eye as a hazy fifth magnitude star, down to NGC 2419, about 5′ diameter and eleventh magnitude. M 13 in Hercules, diameter about 18′ and just about visible to the naked eye as a sixth magnitude star, is the finest globular cluster seen from northern latitudes. ω Centauri is comparable with 47 Toucani in size and brightness.

Globular clusters are strongly concentrated towards the centre, but by counts of stars an elliptical plane of symmetry is shown towards which the variables and bluer stars seem concentrated, suggesting that fundamentally the structure is really somewhat oblate. Although there is similarity of size, form and total luminosity, deviations from the average have been frequently noted. Some, such as Messier 19 and ω Centauri, are elongated in shape, Messier 62 is strikingly non-symmetrical, N G C 4147 has very few giant stars, while nearly a third of these objects are very loose in structure, requiring special examination to show their globular type. Detailed study shows that many intermediate forms exist between the loosest and the most concentrated clusters, and twelve sub-

* A later investigation by Bok and MacRae, however, suggests location of the Sun in a cluster of elongated shape which may lie along a spiral arm of our Galaxy. This is an interpretation of an apparent decrease in star density in the direction away from the galactic centre, with increase and then decrease towards it, and little change in the directions at right angles.

divisions have been decided upon by Shapley as a classification based on concentration towards the centre, Class I being those most marked and Class XII those least marked in this way. The cluster ω Centauri is remarkable for the uniformity in the magnitudes of its brightest stars, a peculiarity shared by N G C 5272, 5927, 6273 and 6656. These clusters are all moderately concentrated (Classes VI to VIII) and two of them, ω Centauri and Messier 3, are the richest of all in variable stars. The various classes are widely spread in apparent brightness and diameter and are not related to the integrated stellar magnitudes except that there is a slight tendency for the less concentrated ones to be faint. This classification by concentration perhaps gives an indication of developmental age and if so should prove useful in studies of the problems of the origin and life-history of stellar clusters.

The numbers of stars contained are of the order of scores of thousands or perhaps even hundreds of thousands. Shapley estimated that the average globular cluster contains more than 20,000 stars brighter than the Sun. On this basis there will be over a quarter million stars, if the proportion of main sequence stars fainter than the Sun is the same as in our vicinity. All spectral types appear to be represented, the colour indices observed ranging from about −0·5 to +2·0. The integrated spectra of the clusters range from A to M, about nine-tenths being, however, in the F5 to K0 classes.

The methods employed for finding distances of the globular clusters have been various. In order of approximate importance they are: the period-luminosity relationship of Cepheid variables; the magnitudes of the 25th brightest stars of a cluster, which range from about 1·3 to 0·9 magnitudes brighter than the short period Cepheids (absolute magnitude zero) this difference decreasing with degree of stellar concentration of the cluster concerned; angular diameters of the clusters' main bodies; and integrated stellar magnitudes. These methods are linked up with each other. The first two are the most reliable; the other two are used to strengthen the determination made from them, and together with the second method, for those clusters where Cepheid variables have not been found or had their periods firmly established.

Table 24 gives data for twelve selected objects; all are situated in galactic latitudes away from the Milky Way zone, for which distances can be more accurately obtained than for those in lower latitudes where the amount of light absorption is difficult to assess. The classification on Shapley's scheme, which is based on concentration to the centre, is given in the last column.

Table 24

GLOBULAR CLUSTERS.

		Distance (*light years*).	*Class* (*Shapley*)
47 Toucani	... ...	25,000	III.
M 13	... ...	31,000	V.
M 5	... ...	33,000	V.
M 15	... ...	37,500	IV.
M 3	... ...	39,000	VI.
M 2	... ...	45,000	II.
M 72	... ...	54,000	IX.
M 53	... ...	66,000	V.
N G C 6229	... ...	98,000	VII.
N G C 5634	... ...	104,000	IV.
M 75	... ...	137,000	I.
N G C 2419	... ...	183,000	VII.

The actual dimensions are much greater than for galactic clusters; the denser parts are of the order of 30 to 100 light years diameter, but the overall dimensions are three or four times as great when measured by densitometer on small-scale photographs. This means that a star as bright as the Sun, situated at the outskirts of an average cluster, would be reduced to fainter than 7th magnitude and be invisible without optical assistance from the centre of the cluster.

The density of stellar distribution is high, perhaps more than a thousand times that in the Sun's vicinity in the central cluster regions; but, nevertheless, the distance of the stars there from their nearest neighbours would with that density average about three-fourths of a light year.* To an observer near the centre the sky would have many stars brighter than Venus appears to us, and in some cases (as there are a few supergiants present more than 1000 times as luminous as the Sun) the sky might have stars giving as much light as a bright Moon does to us.

The stars so far studied in globular clusters are mostly giant or bright main sequence branch stars, the brightest being late type supergiants. Long exposure photographs with the larger telescopes of the future will be able to settle whether there are the usual giant and main sequence branches, as found in galactic clusters and in the stars of our system generally.

* Shapley gives even a much smaller separation. He states that "in the centre of a globular cluster like M13 the separation of one star from another must be less than one hundredth of our distance of 4·3 light years from α Centauri, our nearest known neighbour." (*Harvard Reprint*, No. 272, p. 516). This means a stellar population several million times as dense as in the vicinity of the Sun!

The integrated absolute magnitudes are found to range from about −6 to −9 (photographic) with an average value of −7·5, corresponding to about −8·0 (visual) allowing for colour index. This is equivalent to nearly 160,000 Suns, which suggests a mass for the average cluster of the same order. Recently, however, a much higher value, of the order of a thousand times as much, has been suggested as the result of a mathematical investigation by Finlay-Freundlich, a conclusion rather difficult to accept in view of the total luminosity.

The distribution of globular clusters is very striking. A definite relation to the plane of the Galaxy is shown, and it appears certain that this plane, defined by the faint stars and by the Milky Way Clouds, is also a symmetrical and fundamental place for the globular clusters. They are about equally distributed on each side of this plane and form a large flattened ellipsoidal group 150,000 light years in diameter by about 120,000 in thickness. The centre is in the direction of Sagittarius (galactic longitude 330°) at a distance of about 30,000 light years from us.

The percentages in quadrants of galactic longitude are :—

Longitude 90°-180°	*Longitude* 180°-270°	*Longitude* 270°-360°	*Longitude* 0°-90°
1	15	70	14

The sun is situated towards the edge of the aggregation and this explains the great concentration in the quadrant 270°-360°. Few, if any, globular clusters are to be found within 5000 light years from each side of the plane of the Galaxy, but it seems that this scarcity is due to the effect of obscuring clouds and not to any real absence.

SIR WILLIAM HERSCHEL'S MILKY WAY STUDIES.

In two historic papers, "Account of some Observations tending to investigate the Construction of the Heavens" and "On the Construction of the Heavens," Herschel gave an account of the problem of the structure of our stellar universe, together with the results of about 3300 counts or "gages" of the numbers of stars in fields 15′ diameter, made with his 18·7-inch metallic twenty-foot reflector. It will be interesting to consider briefly, in the light of modern knowledge, what may be inferred from Herschel's pioneer work. He assumed that the extension of our system in any given direction is proportional to the cube root of the number of stars counted in the field of his telescope, which is a perfectly sound conclusion provided there is an average uniformity of size and scattering of the stars and that there is no light obscuration in space. Many writers, such as F. G. W. Struve, Proctor, Gore and Miss Clerke, considered that the disc theory of the shape of our galactic system, thus derived by Herschel, was entirely abandoned by him in his later writings. It is true that a uniform distribution of stars as at first postulated was afterwards admitted to be far from correct, but it would appear better to describe the later opinion of Herschel rather as an admission of great lack of uniformity and that there are many aggregations of stars throughout the system, than as complete abandonment of the idea of a stratum or disc formation.* Serious objections to the shape and size of the section revealed by his counts besides want of uniformity in the spacing of the stars are to be found. In the first place, it was evident from subsequent photographic results (as well as from his later surveys with his four-foot reflector) that the limiting magnitude of the 18·7 inch reflector (about $14^{m}\cdot5$) was not nearly faint enough for the investigation. Secondly, the "cloven-disc" form given by him as the shape of our system is certainly not a physical reality, the bifurcation of the Milky Way on which it is based being an effect of obscuring cosmic clouds. Thirdly, it is possible that there is considerable irregularity in the distribution of the stars throughout the system, the apparent general form of which was described by A. R. Hinks as "no single mass of stars . . . . but an assemblage of more or less distinct clouds of stars tumbled roughly into one plane." The effect of these factors is to render worthless any conclusions as to details of the shape of the Galactic system. Their effect on an estimate of size, based simply, as Herschel's was ,on a unit which is the spacing of the stars in the Sun's vicinity, was to give too small a dimension, particularly in the direction of the system's greatest extension. Accordingly, with the average distance apart of the stars in the solar neighbourhood, about seven light years (see Appendix F), the dimensions of Herschel's section (which is one at right angles to the galactic plane through Aquila to Canis Major), 850 units by 155 units, or 5950 light years by 1085 light years, are evidently much too small.

At the same time, however, study of Herschel's later papers shows that these dimensions were not finally considered to be adequate, particularly for extension in the galactic plane. As one writer (Macpherson, "Modern Cosmologies," page 36) puts it : "at the close of his career he viewed the galactic zone as in the main

* Herschel's view of the disposition of stars in the Galactic stratum could be taken as similar to that of Wright of Durham (the first to suggest a disc theory). In his "Original Theory of the Universe" (1780) he wrote : "Let us imagine all the stars scattered promiscuously, but at such an adjusted distance from one another, as to fill up the whole medium with a kind of regular Irregularity of objects."

an optical effect and the stellar system as a disc vastly more extended than that of 1785." The great pioneer value of Herschel's work is undeniable, and we have in effect stood on his shoulders in order to look further into the depths of space.

THE MAIN GALACTIC STRUCTURE.

We are now in a position to review the state of knowledge regarding the probable shape and scale of our Milky Way system. Shapley's studies of globular clusters and of the galactic star clouds led him to conclusions involving "enormous dimensions of the super-system of globular clusters and of the Galaxy. Once the positions in space are determined, it becomes clear that globular clusters are a part of the Milky Way system. They are associated physically with the system of stars, gaseous nebulae, and galactic clusters which is more or less symmetrically arranged with respect to the equatorial plane of the Galaxy. In measuring the distances of the remotest globular clusters, therefore, we are but measuring the depth of our own galactic system. The one-sided distribution of globular clusters is recognised as an indication of the Sun's very eccentric position in the galactic system. In this same southern part of the sky we find the densest galactic star clouds and the greatest frequency of faint Novae and of other types of distance objects [see Table 12], which is but further evidence of the greater depth of the galactic system in the direction of Sagittarius. Also, in that general direction are some obstructing dark nebulae, which may be wholly responsible for the seeming absence of globular clusters from regions close to the galactic plane. If the obstructing material were removed, we might see clouds of faint Milky Way stars . . . . and globular clusters still more distant than those now known."

Shapley's idea of the dimensions of the Galactic system at the time of his first studies may be described as that of a flattened disc about 300,000 light years in diameter and perhaps 10,000 light years thickness with its centre (that of the system of globular clusters) at 65,000 light years distance from the Sun towards the star clouds of Sagittarius, surrounded by a less flattened roughly ellipsoidal group of globular clusters, nine-tenths of which are contained in a thickness of 100,000 light years ; the stratum 10,000 light years thick being made up of clouds of stars and bright and dark nebulosities.

These conclusions were based chiefly on photometric studies of the magnitudes of various types of stars. The form and size of the Galaxy had been investigated also by statistical methods using star counts, parallaxes and proper motions (for the nearer stars) and radial velocities. The most comprehensive of these statistical investigations was that by Kapteyn (1923) and his results were very different from those of Shapley. He found that the Galaxy appeared to be a vast cluster of stars and involved nebulae of lenticular shape, about 60,000 light years diameter and 12,000 light years thickness, containing about 47,000,000,000 stars, with the Sun near its centre. These figures were only intended by him to be a preliminary outline giving a generalised view. They took no account of the probable clustered nature of the Galaxy nor of irregularities in its general shape. The final results would require to take such factors into account; and it was realised that the photometric study of faint Cepheid variables and other types of stars would considerably modify the conclusions provisionally arrived at by the statistical methods.

The later discovery of an appreciable amount of interstellar light absorption, which was not thought to be of a sensible quantity at the time, showed that this Kapteyn generalised scheme is far from a reality. It also showed that the dimensions of the Shapley system, now considered to be substantially a correct one in its outlines, were considerably too large, a further exaggeration being due to assumption of somewhat too bright absolute magnitudes for the Cepheids used in the measurement of distances of the globular clusters and the dimensions of the system outlined by them.

The most likely value for the overall diameter of the Milky Way system is now thought to be from 100,000 to 120,000 light years, with the Sun's distance to the centre about 30,000 light years and its speed of rotation round that centre approximately 150 miles per second, giving a period of revolution for the Sun of the order of 200 million years—the "cosmic year."

Estimates of the total mass of our Galaxy range from 10^{11} to 2×10^{11} times the Sun's. About half of this is thought to be stellar masses; the other half is dust and gas with perhaps nine-tenths of this half of gaseous constitution.

Recent investigations have shown that the cluster type variables (Cepheid with periods up to 1 day) are found, in considerable numbers, at distances above and below the main Galactic plane, of as great as 30,000 to 40,000 light years. These constitute what Shapley has termed the "haze" or "corona" of our stellar system, and lead to a dimension of perhaps as much as 100,000 light years at right angles to the main stratum of the Galaxy, which includes the globular cluster system also. Density distributions perpendicular to the central plane have been found for stars of absolute magnitudes -2 to $+8$. These show that giants are more concentrated to the middle stratum than dwarfs. For the giants of -2 absolute magnitude the density at 5000 light years distance is only

about 1/1000th of that near the region of the Sun, while for the $+8$ dwarfs the density at about the same distances vertically above and below is as high as 1/20th of that near the Sun.

Co-operative methods of research are now under way which, it is hoped, will lead towards correct ideas of the shape, structure and size of the Galaxy. Two of these may be mentioned as of first-class importance. The first is that due to the selection for the purpose by Kapteyn of 206 special regions evenly distributed over the sky, in which determination of magnitudes, spectra, proper motions, etc., are still being made at several of the world's largest Observatories. The other is a count of stars by magnitudes down to the fifteenth in Milky Way regions; the galactic zone of the sky is divided into a number of sections, each of which is having the attention of a separate Observatory or institution, the scheme being arranged and the results dealt with by Harvard College Observatory.

It is perhaps correct to say that the trend of recent ideas of the structure of the body of the Galaxy can be summarised as follows :—

The notion of a main Galactic system essentially composed of separate stellar agglomerations may have to be abandoned as being chiefly the effect of obscuring matter in the galactic stratum itself. Extragalactic systems, which are presumably all systems of the same sort as our own, do not certainly resemble an accumulation of separate stellar clouds. There are apparently no dynamical effects of a "Local Cloud" or "System" clearly evident in stellar movements, which seem to be governed so far as investigations can as yet say, by the general rotation round the centre in Sagittarius. Owing to the shearing effect of the rotation of the Galaxy at decreasing speeds from the centre, such sub-systems should presumably dissipate in a time much shorter than what is considered to be a permissible period of existence for the Milky Way system, and they would not re-form. In view of these and other difficulties, it may be natural to suppose that the less luminous regions between the apparent star clouds are largely due to obscuring matter, the general cloud-like appearance of the Milky Way being therefore to a considerable extent an illusion. It seems preferable to think of our Galaxy as a flattened system, in all probability with a spiral arm structure, but with the star density varying as a more or less continuous function of the distance from the Sagittarius centre. Fairly considerable local aggregation may exist, which must be regarded only as transitory eddies in a sort of whirlpool, which form and dissipate, and the smaller galactic clusters, of more permanent type, may be gravitationally possible. Absorbing matter which largely produces the appearance of many Milky Way star clouds (and it may be the "Local System") is superposed.

In the foregoing account only a main outline of the chief features of the Galactic structure is attempted. In the opinion of one of our greatest authorities, B. J. Bok of Harvard, the dimensions and total mass are probably fairly well determined. He considers, nevertheless, that there is as yet very little definitely decided regarding details of the system, and that the "big problem on the post-war agenda will be to find out if our Milky Way system is really the huge spiral nebula many astronomers suppose it to be."

As an addendum to this section, reference may be made to recent results of a novel method of research which may assist in investigations of Galactic structure. By means of a large concave metal mirror of more than 30 feet diameter "short wave" (1·87 metre) radiations from Milky Way regions have been studied by Reber of Illinois, U.S.A., who has found that these radiations are strongest from the Galactic centre in Sagittarius with other concentration in the brighter parts and a minimum in Perseus. Since the wave length is relatively great, there is very little absorption due to cosmic dust, and it is suggested that the intensity roughly indicates the amount of material between us and the far edge of the Galaxy. The freedom from absorption should perhaps lead to a better idea of the structure of the Galaxy than can be got by other methods, and these preliminary results may mean that we have here an astronomical tool of some value in the making.

REFERENCES—PART III—CHAPTER I

Author.	*Publications.*	*Subject.*
W. Herschel,	*Phil. Trans. Roy. Soc.*, 1784-5.	Milky Way gaugings.
Shapley,	*Nature*, Oct. 21 and 28, 1922.	The Galactic system.
Shapley,	*Mt. Wilson Contributions* (during years 1915 to 1921).	Globular clusters and Galactic system.
Shapley,	"Star Clusters"	Globular and Galactic clusters.
Shapley,	"Galaxies"	Galactic structure.
Kapteyn,	*Mt. Wilson Contributions*, No. 230.	Scale and structure of universe.
Hubble,	*Mt. Wilson Contributions*, Nos. 241 and 250.	Galactic nebulae.
Trumpler,	*Pub. Ast. Soc. Pacific*, **37**, 307.	Galactic clusters.
Trumpler,	*Lick Observatory Bulletin*, **14**, 154.	Galactic clusters.
Trumpler,	*Astrophysical Journal*, **91**, 186.	Galactic clusters.
Bok,	"The Milky Way"	Galactic structure.
Goldberg and Aller.	"Atoms, Stars and Nebulae."	Planetary nebulae.
Cuffey,	*Pub. Ast. Soc. Pac.*, **52**, 193.	Colour Indices and distances of clusters.

Chapter II

EXTERNAL SYSTEMS—THE UNIVERSE.

On photographs taken with large star cameras and with the big reflectors, hundreds of thousands of nebular images are found, the positions of which show a marked avoidance of low Galactic latitudes. This "zone of avoidance" as it has been termed, is due to the obscuration of dust clouds; it varies in width from about 10° to 40°. The widest part is at Galactic longitude 330° in the direction of the centre of our system, which suggests that there is probably a bulge in the lenticular shape of the main body of our Galaxy, such as is seen on some photographs of edge-on spirals (see Plate 9), the visible Milky Way being at its widest there also.

The research of the past twenty years has definitely established that these nebular images represent stellar systems external to our own Galaxy and situated at distances which range up to many millions of light years. The steps in the ascertainment of this fundamental fact in the constitution of the Universe are outlined in the chapter which follows.

Many lists of these objects have been compiled for different research purposes; but so far only one covering the whole sky. This was made with similar instruments for the north and south skies, and is known as the Harvard survey of nebulae brighter than 13th stellar magnitude. It contains 1249 objects and involved two years' work by numbers of the Harvard Observatory staff. Its penetration into space is to something like 10,000,000 light years.

There has been in progress a deeper Harvard survey with 18th magnitude as the limit, intended to ascertain the details of distribution of these external systems through a very large volume of space and to help in the solution of various related problems. This survey was being carried out with two powerful refractor star cameras, a 24-inch in South Africa and an 18-inch in the States; and it is expected that the total number of galaxies photographed will be not less than about a million, which will extend to more than 100,000,000 light years in depth. It is anticipated that very soon similar and even deeper soundings of space will be possible with the new Schmidt-type reflectors which have the large field of the refractor cameras combined with the speed of the large reflectors.

Five other surveys, not of the whole sky, but of selected areas, have been made to limiting magnitudes 18·5, 19·0, 19·4, 20·0 and

21·5. All but that to $19^m\cdot0$ were made at Mount Wilson Observatory with the 60 and 100 inch reflectors; the exception was the work of the 36-inch reflector at Lick Observatory. The data secured by these surveys provided the material for counts of nebulae in 900 fields well distributed over the surface of the whole of the northern galactic area, and over rather more than half of the corresponding southern area. The counts, reduced to standard conditions for definition, atmospheric extinction at different sky altitudes, and for galactic obscuration, concerned more than 100,000 nebulae and were transformed to numbers per square degree for comparison of the results got by the different telescopes.

The average number of galaxies per square degree photographed at the zenith with an hour's exposure of the 60-inch reflector in the best conditions, for the sky north or south of 40° galactic latitude, clear of the main effects of galactic light absorption, was found to be 109. For the 100-inch similarly the number was 237, the limiting brightness for this instrument with these conditions being $19^m\cdot8$.

It should be remarked that the investigations of Shapley and others have shown that there is no appreciable *intergalactic* absorption of light. Shapley has measured the angular diameters and stellar magnitudes of several thousand galaxies situated many millions of light years away, and has shown that the diminution of brightness with diameter is closely in accord with what is to be expected if intergalactic space is practically transparent. He has also found that selective absorption must be inappreciable. There is added confirmation by the absence of reddening with distance in globular clusters, and by the fact that these objects do not appear fainter in proportion to their diameters or larger in proportion to the brightness of the contained stars than the nearer ones, as should be the case if light were absorbed. Both these investigations make the reasonable assumption that the averages of absolute sizes of the galaxies, and of the globular clusters, are the same in the volumes of space concerned.

The distribution of the nebulae from the small-scale aspect as derived by these researches is markedly non-uniform. They are seen singly and in groups of increasing numbers up to great clusters of thousands of members. But when samples of very large numbers are considered, and in terms of very great volumes of space, the clustering tendency gets smoothed out and the distribution approaches a large-scale uniformity, although down to faint magnitudes there are still evidences of some enormous groupings. Down to moderately bright magnitude it is found that the stars greatly outnumber the nebulae; but at the faintest limits the number of nebulae per square degree gets comparable with the number of stars

photographed. For instance, photographs taken with the 100-inch at the galactic pole, where galactic obscuration is least, show about 2400 nebulae per square degree, a higher number than the stars on the plates; and it is considered by Hubble that there are probably 100 million nebulae in the entire volume of space out to the limit of distance concerned.

There is much diversity in size and brightness, and they range from a few very bright ones, such as the Andromeda nebula, M 31, which is about 3° in diameter over its brighter parts and visible as a hazy spot to the naked eye, down to multitudes of tiny specks on long exposure photographs with the large reflectors.

It was only by photography that details of the structure of the larger specimens could be ascertained for purposes of any classification that might be possible. Several schemes have been published of which the one due to Hubble may be briefly described. His scheme involves a series in three broad types, elliptical (or spheroidal as Shapley prefers to call this type), spiral, and spiral with a luminous bar crossing the nucleus and the surrounding disc of nebulous light.

The three types may be represented by a Y-shaped diagram. The stem is the elliptical or spheroidal series, starting at the foot with specimens of circular outline and progressing to more elliptical forms. One of the arms is the spirals; it begins with those which have the arms closely disposed passing to others with the arms more openly spread and more distinct; and the other arm is the so-called "barred spirals" of types which correspond to the graduations of openness in the normal spiral branch. The first of the three types are designated E0 to E7 as oblateness increases; the second Sa, Sb and Sc; and the third SBa, SBb and SBc. In the E type or class it may be taken that they are all ellipsoidal or spheroidal of various degrees of oblateness and not in any case a torpedo-shaped body, which would not be gravitationally stable. In the spiral types the arms are found on close examination to be enhancements on the background of light surrounding the nucleus; and it has also been shown that the light from the arms does not constitute as large a fraction of the light from outside the nucleus as was first thought. Observation has not yet certainly shown what is the direction of rotation of the spiral arms; *i.e.*, whether this occurs with the convex side forward or the reverse, and it is not known whether the points of junction of the arms with the nucleus advance, are stationary or regress in space. Such evidence as is available, however, strongly suggests that the convex sides of the arms are in the front of a rotational movement.

There is also a relatively infrequent Irregular type, the Magellanic Clouds being the brightest examples. A peripheral band of obscuring matter (presumably dust or gas or both) is often found in the Sa and Sb types, most clearly indicated when they are edge-on or nearly so (see Plate 9).

On photographs of bright spirals and Irregulars taken with the largest reflectors under the best conditions, star images are numerous; but until lately the ellipsoidal E-types and the central regions of spirals had not been resolved into stars. Any stars shown were O or B type giants and supergiants, about 1000 to 40,000 times as luminous as the Sun, and they are brightest in the Sc or Sb classes of nebulae; no stars had been found in the Sa class. It was none the less considered that all classes are probably composed largely of stars, and that these stars are not bright enough to be distinguishable except in the cases mentioned. This idea has received strong support from recent photographs taken with the 100-inch reflector, using red-sensitive plates, of the central regions of M 31, and of its two companions M 32 and NGC 205, which have been thus partly resolved so as to show masses of reddish stars (similar to K-type giants), estimated to be about 500 times as luminous (photographically) as the Sun. It should be noted, however, that the integrated spectrum of M 32 is of a type resembling a G 3 type dwarf-star, according to Sinclair Smith, who had previously studied this smaller galaxy on plates of the ordinary kind taken with the 100-inch reflector, and had concluded that there are perhaps 20,000,000 stars in it, the bulk of which are of a somewhat hotter type of spectrum than the reddish giants, that have so far shown on red-sensitive plates.

Two other objects that are nearby galaxies, NGC 147 and NGC 185, have also been partially resolved similarly and there seems strong hopes that with the aid of the Palomar 200-inch reflector and the new technique all the nearer galaxies will be at least partly resolved.

The order of appearance of stars in photographs of galactic systems may be described as follows:—Supergiants and giants are found in the outer regions of spiral systems; main sequence, and perhaps giants also, in their nuclear regions; and in the ellipsoidal type the stellar composition seems to be similar to that of the nuclear regions of the spirals. Among galaxies in general the relative distribution changes systematically through the sequence of structural forms, the brighter supergiants being found closer towards the centre as the degree of openness of the spiral arms becomes greater. It may thus be said that if the order of stellar evolution is from supergiants and giants towards and through the main sequence, the evolution of the galaxies themselves is not necessarily from ellipsoidals to spirals of increasing openness, but conceivably the reverse of this. The practicability of a general classification of galaxies into ellipsoidal and spiral types cannot, of course, be taken to prove that one type developes into a succeeding type of the series, in an evolutionary sequence. The giant and main sequence stellar distribution among the various types as mentioned, and the fact that the spiral arms appear as enhancements which may have as it were grown out of the material of the nebulous background, suggest at least a possibility that the evolutionary order might turn out to be from Irregular through spirals to the ellipsoidal kind.

Globular clusters have been found (as was suggested should be the case in an earlier edition of this book) in several of the brightest galaxies such a M 31, M 33, M 101, NGC 6822, the Magellanic Clouds, and others. They are generally not so large or luminous as those of our own Galaxy, their absolute magnitudes ranging from -4 to -7 as against the Galactic range of -6 to -9. In general, the spectra of the galaxies are similar to that of the Sun; the H and K lines of calcium, the G-band of iron and some hydrogen lines can be distinguished. The spectra of the E class are generally of G type, and those of the spirals from G 3 to F 9, the earlier types on the average with the more open galaxies. Many of the spirals, but very few of the ellipsoidal, show bright lines due, no doubt, to the presence or absence of gaseous nebulae and of the high temperature stars which cause the emission.

The colours of all types, except the Irregulars, are rather redder than would be expected from the spectral type, *i.e.*, the colour indices are greater than the normal for the spectrum and the colour classes correspond to somewhat redder and cooler types of stellar spectra. But there is no satisfactory explanation of this; there is no intergalactic selective absorption to account for it, although local absorption in their own structures might perhaps be responsible.

As regards details of the colours inside a particular galaxy, a striking difference is found between the nucleus and the arms in spirals. For M 51 (NGC 5194, see Plate 10), an Sc spiral, Carpenter found a strong increase towards the blue end of the spectrum between the nucleus and the arms, the colour index varying from $+0^m{\cdot}6$ near the nucleus to $-0^m{\cdot}3$ about one revolution of the spiral arms from it. This is what would be expected if the hotter type stars were in the arms and the cooler ones nearer the central regions. In the case of M 82, an I or irregular type, there was no essential difference found between the inner and outer parts.

On classifying 600 of the brightest specimens, Hubble found that about a sixth are ellipsoidal; the remainder are all spirals, with the exception of 2½ per cent. of the total classed as Irregulars. These proportions are about the same as are shown by the thousand brightest of the 13th magnitude Survey by Shapley and Miss Ames.

In the clusters of hundreds of nebulae, twenty-five of which are known, all types of galaxies are present; but the ellipsoidal kind seem usually to predominate. One of the richest, that in Coma, has about 2000 members. A hundred or so groups composed of fewer members have also been noted; one of these contains our Galaxy and at least twelve other systems.

Determination of Distances and Dimensions.

The first effective steps in this were due to the discovery of Novae in a few of these nebulae less than 30 years ago; this indicated that distances were probably of the order of several hundred times that of the average galactic Nova, itself a distant object. This was followed by identification of stars, of a type known to be highly luminous, in the larger spirals; and in 1922-3 by the detection of Cepheid variables in M 33, NGC 6822, and M 31. The distances being derivable from the Cepheid period-luminosity relationship, a search for these variables in other large spirals soon led to a knowledge by this period-luminosity relationship of the distances and dimensions of the nearer and brighter objects. The stages in the determination of distances and dimensions of these nebulae were as follows:—The brightest stars in the nearby galaxies, in about 10 of which (all within a million light years from us) they could be closely studied, were found to be generally of a fairly uniform luminosity—roughly 48,000 times that of the Sun (or −7 absolute magnitude). This criterion was applied to the members of clusters of nebulae, as in some of these individual stars could be detected even although it was not possible to define their types. Thereby distances up to several million light years could be ascertained; the Virgo cluster of several hundred was thus found to be 7,000,000 light years away. Measurements of the luminosities of the individual brighter nebulae in all such clusters also showed an approximate uniformity from one cluster to another, of 100,000,000 times the Sun (or −15 absolute magnitude); this provided a method for finding distances of faint nebulae where, owing to great remoteness, separate stars could not be seen. Distances of clusters of nebulae as far away as a hundred million or more light years could be detected in this way; the faintest nebulae photographed by the Mount Wilson 100-inch are thus known to be something like 500 million light years from us. (See Appendix J).

The distance of any very remote faint galaxy, too far away to show Novae, non-variable stars of high luminosity, or Cepheid variables, cannot be individually determined, however, with any reasonable degree of accuracy, by these methods. This is owing to the very considerable range of luminosities of the individual galaxies, over more than five magnitudes, although the great majority are not far from the average value. A distance based on an assumed absolute magnitude for an individual galaxy (say an average absolute magnitude of −15) would, therefore, be subject to large unavoidable possible error, as no means of classifying a faint specimen as a giant, normal, or dwarf of the species is available.

Hubble has determined the average real dimensions of the main bodies for the various types. He gives 2000 to 5000 light years for the E0 to E7 classes, 6000 to 10,000 light years in the case of the spirals, the values increasing with greater openness of structure (Sa to Sc and SBa to SBc), and about 6000 light years for the I or irregular class. It should be noted that these dimensions, which are for the larger axes of form, do not refer to limiting or overall sizes; Shapley has found mean diameters of 13,000 and 16,000 light years for spheroidals and spirals respectively from densitometer measurements of photographs.

There is a great range in size, although the majority are close to the median size. For example, M 31 is about 40,000 light years in length and 9000 in breadth over its brighter parts; but over all, including an outlying haze of stars, the dimensions are 60,000 by 54,000 light years, demonstrating that it must be a giant comparable in size with our Galaxy, also a giant, if not indeed a supergiant, system.

Internal Motions and Masses.

The determination of the masses of the galaxies is a problem of the greatest importance in discussing the nature and history of the stellar universe. Several methods have been employed. One is based on the total luminosity of a system. Taking an average absolute magnitude of −15, or equal to 100,000,000 Suns, and assuming that half of the mass is stars and the other half gas and dust (Bok's estimate), also that the average unit of stellar mass of the Galaxy radiates light at the same rate as a similar unit of solar mass, the total mass of a typical Galaxy would be that of 200,000,000 Suns (2×10^8 Suns).

Another, and probably more reliable method is based upon spectrographic measurements of radial velocities at points along the major axes of some of the brighter objects, that happen to be placed edge-on, or nearly so, to us. Mass can thus be estimated for the material between a given point and the centre of a galaxy in much the same way as the Sun's mass is found from orbital motions of the planets. But the spectrographic results are difficult to interpret, as we do not yet know how the stars and other material are distributed in relation to the points for which the velocities have been measured.

Recent studies of M 31, M 33 and other spirals have produced rather uncertain results. For M 31 (undoubtedly a very large specimen) a mass of about 10^{11} times that of the Sun has been found; and for M 33 (probably rather larger than the average) 2×10^9 the Sun's, or only a fiftieth of M 31, although the ratio of luminosities is a tenth. The mass for M 33 is, however, about ten times that derived above for the average spiral from luminosity. There does not appear to be any method open for reconciliation of this rather great difference, except by the attribution of a very large fraction of low-luminosity stars of relatively large mass and/or non-luminous matter such as gas, dust or other dark bodies.

Another method has been used involving analysis of the spectrographic radial velocities of 32 members of the Virgo cluster. The recessive radial velocities, which range from about 600 to 900 miles per second, do not seem to be connected with magnitude or position in the cluster and this has been taken by Sinclair Smith, the investigator responsible, to indicate that the cluster is dynamically a stable system. Assuming the greatest peculiar velocity to be that of a body describing a circular orbit, or to be the velocity of escape from the cluster, this gave the total mass of the galaxies in the cluster and, when divided by the number of galaxies contained, the average mass per galaxy. The value found, 2×10^{11} that of the Sun, is more than 10 times what appears probable from the two methods already described, and at present there is no obvious means of reconciling the figures. It is of interest to note that the total mass of our Galaxy, perhaps a very large Sc type spiral, is considered to be of the same order, from calculation based on its rotation; and that that of M 31, a large Sb type, found from the spectrographic method, is similar.

Periods of rotation at different points outwards from the centre have been found for several galaxies by the aid of spectrographically measured radial velocities; for M 31, 11 million years for the core and 92 millions for the outer regions; and for M 33, 59 millions and 200 millions similarly. These periods, although generally shorter, are of the same order as that found for the stars in the Sun's vicinity, round the Galactic centre (200 million years). In both M 31 and M 33, however, there is no evidence of central condensation of mass provided by the measured rotation periods, and this may throw some doubt on the generally accepted idea that our Galaxy has such a concentration. In these two systems the rotational velocities, except for a short distance near the centre of M 31, increase outwards from the centre, decrease only showing itself far out from the nucleus, like the decreasing rotational velocities observed in the neighbourhood of the Sun, which is evidently in a position well out from the centre of our system.

Clusters of Galaxies.

As already stated, more than 25 of these are now listed, but Hubble considers that, in surveys down to the 20th magnitude, probably one for each 50 square degrees of the sky, or perhaps a total of 600 clusters allowing for the obscured part of the sky, would be found. Those known are composed of hundreds of galaxies (2000 or more are believed to be in the Coma cluster) with a range of about a hundredfold in their luminosities (five magnitudes). All types are represented, usually with the ellipsoidal class the most frequent, and more concentrated towards the centre of the clusters than the other types. The distances of a selected number of clusters are as below :—

Table 25

Cluster.	*Distance (light years).*
Virgo - - - -	7,000,000
Pegasus, - - - -	24,000,000
Hydra, - - - -	24,000,000
Cancer, - - - -	29,000,000
Perseus, - - - -	34,000,000
Coma, - - - -	45,000,000
Ursa Major, - - -	85,000,000
Leo, - - - -	117,000,000
Corona Borealis, - -	130,000,000
Bootes, - - - -	240,000,000

An idea of the size and contents of one of these clusters has been published by Zwicky. He remarks that the cluster in Coma has 2000 or more members; 650 of these, all 100,000,000 times the Sun's luminosity, have been photographed with an 18-inch Schmidt reflector. The overall diameter for the volume occupied by the galaxies considered is about 5,000,000 light years, and the distance to its nearest neighbours of each galaxy in it will average about 300,000 light years or six times as close as for the "unclustered" galaxies of space. (See Appendix L). However, Zwicky has suggested that practically all the galaxies may be contained in more or less regular clusters. He remarks that about twenty clusters are known within 40 million light years distance, and that if these clusters are really large enough to fill the volume, each has a diameter of about 25 million light years and contains from 2000 to 4000 individual members. If this idea is correct there should be about 30,000 such clusters accessible to the 100-inch reflector.

According to Shapley, however, the dimensions of the nearest, and one of the best explored, of these clusters (that in Virgo) are much less—only about 1¼ million light years in diameter; it contains about 250 galaxies according to the same authority. But it seems possible that these figures might be augmented by means of photographs taken with Schmidt cameras.

The Local Group.

As has been remarked earlier, about 100 groups, each composed of a few galaxies, have so far been noted. The most important of these to us is the one to which our Galaxy belongs. The limits of this group are taken to be roughly a million light years from our system; and the nearest of the galaxies outside of the group is about 2½ million light years away. In this connection it may be remarked that Zwicky has stated that the group may be actually part of the nearest cluster—that in Virgo—presumably situated well out from its centre.

The volume in space occupied by the group is approximately ellipsoidal in form, with M 31 near one end of the major axis and our Galaxy near the other end.

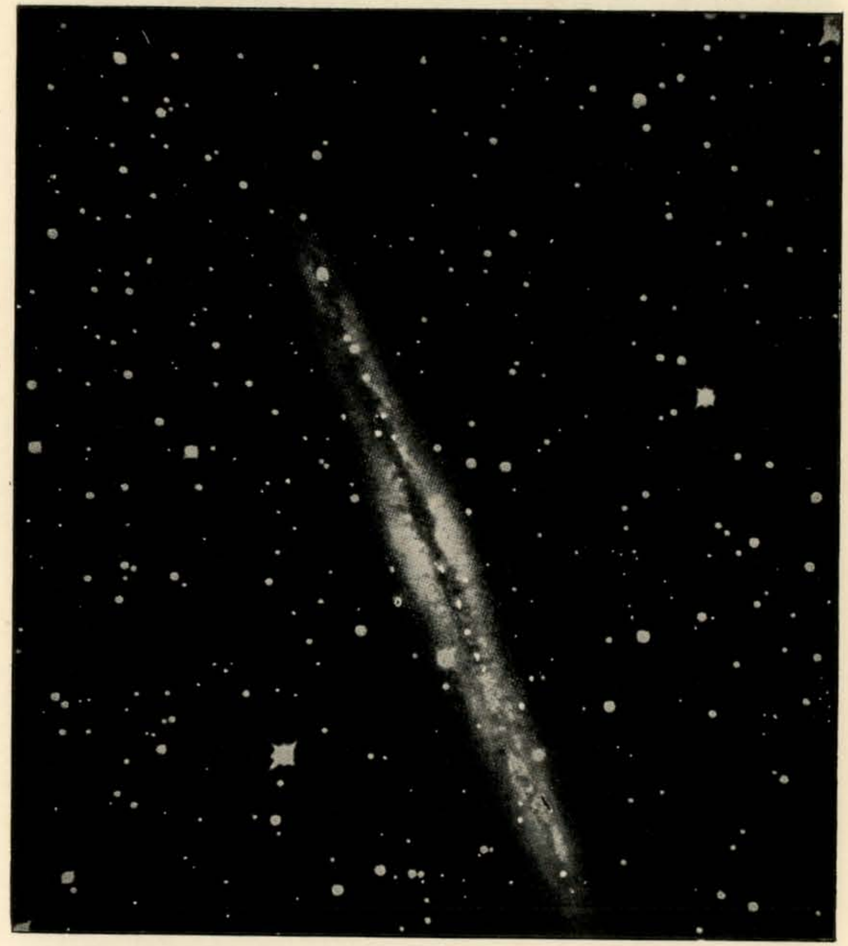
Table 26 gives particulars of the members so far discovered.

Table 26

Members of the Local Group of Galaxies.

Object.	*Type.*	*Distance. (light years).*	*Absolute Magnitude.*	*Diameter (light years).*
Our Galaxy	Sb or Sc ?	—	(− 20 ?)	100,000
M 31	Sb	750,000	− 17·9	40,000
Magellanic Cloud	I	72,000	− 15·9	15,000
M 33	Sc	780,000	− 14·9	14,000
Magellanic Cloud	I	82,000	− 14·5	12,000
M 32	E2	750,000	− 12·9	3,000
Fornax System	E	470,000	− 11·9	6,500
NGC 205	E5	750,000	− 11·5	3,500
NGC 6822	I	525,000	− 10·8	3,000
IC 1613	I	730,000	− 10·8	3,500
Sculptor System	E	225,000	− 10·6	3,000
NGC 185	E	670,000	− 10·6	2,800
NGC 147	E	670,000	− 10·3	2,700

The average absolute magnitude of the members of the group is − 13·3, or more than a magnitude fainter than what is assumed as the average for all galaxies. This is because of the presence of so many faint members; but it is rather difficult to believe that there may not be many more of the abnormally faint type in space



Mount Wilson Observatory.

Plate 9—NEBULA, NGC 891.

An edgewise spiral galaxy in Andromeda; distance about 8,000,000 light years (Lundmark).

Mount Wilson Observatory.

PLATE 10—NEBULA, CANES VENATICI
NGC 5194-5.

A spiral galaxy seen at right angles to its plane ; distance about 2,000,000 light years.

than have been so far found, and that −15 or −14 absolute magnitude, generally used as the average, may not be somewhat high. Another apparent inconsistency is found in the very different proportions of numbers of galaxies of the different types shown in Table 26 as compared with the general field. In the latter, the proportion is for spirals, ellipsoidals and irregulars, nearly five-sixths, about one-sixth and one-fortieth respectively (see page 131). In the local Group, the proportions are very different from this. For the same types they are less than a quarter, nearly a half, and nearly a third. Of course, the number of objects in the Local Group is a small total, but nevertheless the two discrepancies of magnitude and type are there. On the other hand, Hubble states that a "careful re-examination of the surveys demonstrates that such nebulae [the fainter type] would be detected if they existed in considerable numbers. . . . The presence in the Local Group appears to be a unique feature, and they detract from its significance as a fair sample of nebulae in general." Nevertheless "the fact that the Galactic system is a member of a group is a very fortunate accident," leading to the possibility of closer study of the different types.

A short account of the chief characteristics of these nearby galaxies follows, in order of distance.

THE MAGELLANIC CLOUDS OR NUBECULAE.—These objects, resembling to the naked eye two detached portions of the Milky Way (there is, however, no visible connection) are situated in R.A. $5^h\ 18^m$, Dec. −68°·7 (Nubecula Major) and R.A. $0^h\ 50^m$, Dec. −73°·5 (Nubecula Minor). The galactic co-ordinates corresponding are, respectively, 247° long., −33° lat., and 268° long. and −44° lat. Known to the ancients, the greater Cloud is referred to by Al-Sufi (tenth century) as the "White Ox" (*el-baker*). It is considerably the brighter to the naked eye, Sir John Herschel finding that "strong moonlight . . . totally obliterates the lesser, but not quite the greater." They are both round or oval to unassisted vision, although the Nubecula Major presents "the appearance of an axis of light, very ill-defined, and by no means strongly distinguished from the general mass, which seems to open out at its extremities into somewhat oval sweeps, constituting the preceding and following portions of the circumference." (*Outlines of Astronomy*, page 655). Miss Clerke describes this appearance similarly :—"To the naked eye it shows vaguely a brighter axis, spreading at the ends so as to produce a resemblance to the Dumb-Bell nebula." (*System of the Stars*, page 51). The nebula 30 Doradus is visible as a small bright patch in the following part. According to Sir J. Herschel, the areas occupied are 42 square degrees (Nubecula Major) and 10 square degrees (Nubecula Minor), but recent long-exposure small-scale photographs show very much greater areas.

The dominating feature in both is an elongated patch of densely crowded stars. Star clusters of the globular and open types, and considerable numbers of gaseous nebulae have been observed in both systems. Thirty-two O-type stars, ranging from $9^m{\cdot}9$ to $14^m{\cdot}0$ (photographic) are contained in the Nubecula Major and nine stars of the P Cygni type (a class of star with bright line spectrum resembling that of a Nova), from $9^m{\cdot}5$ to $13^m{\cdot}0$ (photographic); while the Nubecula Minor is known to contain at least one O-type star. A plot of these 41 stars in the Nubecula Major covers an elliptic area 6° by 4°·3; the major axis is in position angle 130°, not very different from the angle 120° found for the brightest elongated part of the Cloud.

Estimates of distances are given in Table 26. They correspond to distances of 41,000 and 57,000 light years to the south of the galactic plane. Their true space separation is about 30,000 light years, centre to centre.

There are many very remarkable objects in the Clouds. For example, the nebula 30 Doradus in the Nubecula Major seems to be the largest known gaseous nebula, being much larger absolutely and brighter than the great nebula in Orion, which it outshines 9000 times. According to Shapley, if it were placed in the constellation of Orion more than all of which it would cover, it would give as much light as 200 stars like Sirius and cast perceptible shadows on the Earth.

Then the eclipsing binary star S. Doradus is 300,000 times (the two components together) as luminous as the Sun, *i.e.*, the components radiate at a rate entailing loss of mass of over a million million tons per second! In the larger Cloud there are more than 20 stars each at least 150,000 times as luminous as the Sun; while others—K and M variables—in the two Clouds are of such brightness and colour as to suggest that they are larger than Betelgeuse, which is 360 million miles in diameter.

More than 30 globular clusters have been found in the large Cloud and a few in the other. The radial velocities of the Clouds, determined spectrographically from bright lines in gaseous nebulae in the two systems, show when analysed that the Clouds move in space at right angles to the direction of the Sun's galactic rotation with a speed of 300 miles per second, this being parallel to a tangent to the edge of our Galaxy assumed to be circular in shape.

THE GALAXIES IN SCULPTOR AND FORNAX. These were discovered in 1938 by Harvard astronomers. They are both composed of swarms of stars, slightly concentrated towards their centres.

That in Sculptor has 10,000 stars in it brighter than $19^m{\cdot}5$; very few are brighter than $18^m{\cdot}0$, so that there are no supergiant stars. Some Cepheids are present, giving the distances shown in Table 26. There is no structural detail discernible beyond the concentration referred to. The Fornax galaxy has several globular clusters in it. After the discovery of these two galaxies a search with a special camera was made to ascertain if more of such systems were to be found. None was discovered, but it would be very difficult to identify objects of the class if more than several million light years away, owing to their loose and inconspicuous aspect.

NGC 6822. This is an object very similar to the Magellanic Clouds, discovered originally by Barnard visually, at R.A. $19^h 41^m$ Dec. −15°, 20° from the centre line of the Milky Way. By the bold assumption of an analogy between this object and the Magellanic Clouds, Shapley at first estimated a distance "of the order of a million light years," this estimate being based on its angular dimensions, size and luminosity of its involved nebulae, and magnitudes of its brightest stars. Hubble has made an elaborate study from photographs taken with the 100-inch Mt. Wilson reflector. He finds total apparent angular dimensions of 20′ × 10′, with a brighter core, 8′ × 3′, similar to this feature in the Nubeculae. Many general structural similarities with the Magellanic Clouds are noted, and from eleven Cepheids, ranging in period from 64 to 12 days, and in magnitudes at maximum from $17^m{\cdot}45$ to $19^m{\cdot}05$, the distance in the Table has been estimated. In this galaxy several patches of gaseous nebulosity with emission lines have been noted; one is over 100 light years in diameter.

NGC 147 and NGC 185. Recently these have been found to be dwarf galaxies, by means of photographs taken with the 100-inch reflector on red-sensitive plates. The first-named is a large star cloud with little condensation; the other is an ellipsoidal galaxy, now partly resolved into stars for the first time.

NGC 1613. This is another dwarf, resembling NGC 6822, with many Cepheids and other variables, but with the patches of nebulosity less conspicuous.

M 31, M 32 and NGC 205. M 31 is a giant Sb spiral; the outer parts are resolved into dense swarms of stars on photographs taken by the 100-inch on ordinary plates. All of these stars are giants or supergiants; the least bright has two or three hundred times the luminosity of the Sun. Many Cepheids and Novae and one Supernova (1885) have been observed in M 31. M 32 and NGC 205 are ellipsoidal galaxies, E2 and E5 respectively. They have been partially resolved on red-sensitive plates into reddish giant stars, no doubt only the brightest of their stellar populations.* The three galaxies are relatively close together in space, but only the minimum distances apart as projected on the sky can be definitely known. This minimum is 5000 light years between the centres of M 31 and M 32; the figure for NGC 205 is 8000 light years. If they all lie in the plane of M 31 (which is inclined about 15° from the line of sight) the separating distances are 13,000 and 32,000 light years respectively. More than 200 globular clusters in M 31 are known; the absolute magnitudes range from -4 to -7 with diameters of 12 to 50 light years, comparable with the figures for the globular clusters of the Magellanic Clouds but systematically less bright and smaller than those in our Galaxy. Two maxima are found at -5 and $-6{\cdot}2$, and the range of -4 to -7 and that for our galactic system (-6 to -9) overlap to some extent, suggesting the possibility of the existence of sub-classes of globular clusters whose relative richness varies from system to system, with more of the brighter type attached to our Galaxy than to M31 or to the Magellanic Clouds. Their distribution follows that of the luminosity of the spiral, unlike the roughly spherical one of the globulars round our system. There are also a few open clusters, one 50 light years in diameter.

MESSIER 33. Photographs with the 100-inch Mt. Wilson reflector resolve this Sc class spiral in many places into stellar images in no way different from those of ordinary faint galactic stars. Forty-five variables have been found; 35 are Cepheids of periods of 13 to 70 days and photographic magnitudes at maximum of from $19^{m}{\cdot}1$ to $18^{m}{\cdot}0$. Of the remaining 10 variables, 4 are irregular, and one is probably eclipsing. Two Novae of maximum photographic magnitude $17^{m}{\cdot}25$ and $17^{m}{\cdot}9$ respectively have also been observed. Patches of diffuse nebulosity with white or bluish stars, apparently of 0 or B type, are situated in the spiral arms. The angular extent of these patches and the apparent magnitudes of the involved stars are related as in the case of galactic nebulae (see page 107). Comparison of photovisual with photographic magnitudes shows the colours of the brightest stars in this galaxy to be white or bluish, unlike those in the galactic globular clusters which are yellow or red. Star counts down to $19^{m}{\cdot}2$ (photographic) indicate that stars are first observable at $15^{m}{\cdot}5$, and that the relative frequency of stars of different grades of luminosity is similar to that found for supergiants

*Baade, to whom these results are due, divides stellar populations into two types. One of them contains high temperature supergiants (absolute magnitudes as high as -5 or -6), and a higher proportion of binaries, but less novae and supernovae than the other, in which the most luminous stars are giants (absolute magnitude -2) of low temperature. The former type is observed in the arms of spiral galaxies but not in their central regions; the latter in the central regions of spirals, in ellipsoidal galaxies, between the arms in spirals, and in globular clusters.

and giants in the solar vicinity. The linear (projected) separation of M33 and M31 is about 20,000 light years; they would each be a fine object as seen from the situation of the other.

A Dip Into Space.

To show how specimens of some of the objects dealt with in the preceding pages are to be found in an apparently rather uninteresting small part of the sky, visible on every clear night in northern latitudes, the Bowl of the Dipper, *i.e.*, the quadrilateral formed by α, β, γ and δ Ursa Majoris, may be examined. The area is roughly 45 square degrees or rather more than a thousandth of the entire sky. The stars at three of the corners of this window into space, β, γ and δ, are all A-type main sequence from 55 to 20 times the Sun's luminosity, at about 80 light years distance and members of the Ursa Major moving cluster. The other star, α, is a close binary pair, consisting of a primary giant K-type, with a companion revolving round it in about 40 years, which is visible only with large telescopes. There is an eighth magnitude star about 6½ minutes of arc to the south-west; this is, however, probably not physically connected.

If we assume the quadrilateral α, β, γ, δ to be a frame 80 light years distant, the longest side is α to δ and the shortest δ to γ; the former is approximately 13 light years wide and the other about 6 light years. So much for the frame round the area and for the nearest objects concerned.

Closer scrutiny reveals to good eyesight about a dozen faint stars; at a fifteenth of the limit of naked eye vision (9th magnitude) a hundred or so stars are visible; while at a thousandth (13th magnitude) there are something like 3000 stars to be seen; and at a millionth (21st magnitude—the limit of the 100-inch photographically) about 150,000 are to be found. Less than a degree south of the centre of the quadrilateral, there is a double star Struve (Σ) 1553, composed of $7^{m}{\cdot}3$ and $7^{m}{\cdot}8$ stars separated by about 5 seconds of arc. Slightly outside the area about 2° south following is the planetary nebula Messier 97, of circular shape, 3¼ minutes of arc in diameter, named the Owl nebula owing to two darker spots in it resembling eye-sockets; its distance is not known. Inside the area there are twelve nebulae, brighter than 13th integrated magnitude, probably all external galaxies relatively near to us on the larger cosmic scale, and one small faint but well defined planetary nebula, all objects visible with telescopes of moderate optical power; and there is one considerable Sb type, patchy spiral nebula, just on the southern border about 1° south following β, between that star and the Owl nebula, NGC 3556, 8′ long by 1½′ broad. Assuming it to be of average luminosity and dimensions it must be at a distance of several millions of light years.

The distances of the stars other than the four bright enclosing ones are to be expressed in terms of hundreds or of thousands of light years; and there are about a hundred small hazy luminous patches, galaxies far beyond the limits of our own Galaxy. Many of these can be detected only on photographs taken with the largest telescopes. Not far from the centre of the bowl there is a concentrated cloud of faint galaxies at a distance, according to Baade, of 150 million light years.

We thus look out through this frame and find inside it, or very close thereto, a binary pair, and two planetary nebulae; and many external galaxies ranging in distance from several million to 150 million light years. No doubt other interesting objects can be found, while intensive search with photographs made by the 100-inch, would show even more distant galaxies such as have been found in other directions.

Red-Shifts and their Meaning.

The first critical measurements of the positions of lines in the spectrum of an external galaxy were obtained by Slipher in 1912, using the 24-inch refractor of the Lowell Observatory. He continued the work, and by 1925 had measured displacements of the lines for forty-one objects, two others having been by then measured elsewhere. The values turned out to be generally larger than that for any star, and all except 10 per cent.* were towards the red end of the spectrum, *i.e.*, they were generally shifts which might be taken to indicate movement away from us. The distances of these galaxies had been estimated (as described in an earlier section), and Hubble was able to derive a relationship between these shifts and distances which, treating the shifts as measurements of velocity, showed an increase of 100 miles per second for each million light years of distance. It was then seen that, if this "velocity-distance" relation continued for objects still further away than the most remote of the objects so far measured (the Virgo cluster), these shifts could be used as distance criteria, or as checks on distances otherwise derived. By the year 1936 more than 200 values of red-shift for galaxies had been secured; the greatest corresponded to a speed of 26,000 miles per second for a member of a cluster of galaxies believed to be about 240,000,000 light years away.

Up to the present the only known cause for the red-shift is

* These referred to objects all in one region of the sky with an apparent velocity of approach, later practically accounted for by the rotational velocity of the Sun round the centre of the Galaxy.

motion away from us; and many authorities consider that the explanation is really such a motion, indicating an expansion of the universe whereby every galaxy, wherever it is, is receding from all the others. But some do not favour this as the explanation,* although everyone is aware that if it is not correct, some entirely new physical process may need to be discovered to account for the phenomena.

Red-shifts mean a loss of energy in the light before it reaches the observer—for two reasons if the galaxies are receding; firstly, a reduction of energy in each quantum of radiation because of increase in wave length, and secondly, owing to recessive movement and the receipt by the observer of a smaller number of quanta per second. But if the galaxies are stationary, only the first of these will apply. The cause of what is observed may be either at the galaxy itself, or act during the transit of the radiation through space. If the latter is the case, then the galaxies are stationary in space, apart from any smaller individual motions, and the radiation loses energy by some undiscovered process in proportion to the length of its journey. The problem reduces itself in one aspect to the determination of whether or not the galaxies are actually all moving away from each other. In principle a solution of this is possible, since a receding galaxy, having its spectrum shifted to the red, must photograph fainter than one which has no movement (the part of red-shift due to motion being then not present) at the same momentary distance. The reduction in brightness would be negligibly small for low speeds, but would increase with velocity and become of a nearly measurable amount at the limit of distance to which the 100-inch reflector can reach.

To be able to calculate definitely what would be the stellar magnitude of a galaxy, if stationary or if receding, it would be necessary to know its actual distance. This is unfortunately not possible, as the only method of estimation of great distances is by means of the observed magnitudes themselves. Hubble's summary of the position as it appears to him is clear and concise. He says: "Nevertheless we can approach the question indirectly. From the measured apparent faintness, we derive two scales of distances corresponding to the alternative interpretations of red-shifts. We may, of course, use either scale and accept the small differences as uncertainties in the investigations. Again, we may explore the observable region—determine the distribution and the law of red-shifts as accurately as possible—using, first, the scale of distance

* For instance, Zwicky has suggested a "gravitational drag of light" (as light has mass) when it passes the matter throughout space; and MacMillan, loss of energy of light photons either because of inherent instability or through collisions with other photons. These suggestions are all equivalent to a decline in frequency, *i.e.*, reddening, during transit.

for stationary nebulae, in the hope that the wrong scale may lead to inconsistencies that can be recognised or suspected.

"The programme has been carried out, but the results are not definite. Using the stationary scale, the distribution is uniform and the law of red-shifts is linear. Thus we reach a consistent picture of the observable region as thoroughly homogeneous—the sample, although to us it seems vast, is too small to indicate the nature of the universe itself. The conclusion seems reasonable, and even familiar, but in such a universe we do not know how red-shifts are produced. On the other hand, if we assume that the nebulae are receding, the apparent distribution is no longer uniform (the density increases outwards), and the law of red-shifts is no longer linear (red-shifts increase with distance at an accelerated rate). These complications suggest an expanding universe that is curiously young and small.

"Thus, these results, at the moment, seem to favour the conception of a stationary universe, but they do not definitely rule out the possibilities of an expanding universe. Judgment is properly reserved until further information becomes available. The 200-inch reflector, destined for Mount Palomar, should furnish the necessary data. It will penetrate so far into the universe around us, and red-shifts will reach such dimensions, that the dimming factors of recession, if they are present, should be unmistakable."

It may be remarked that in these investigations the observed stellar magnitudes of the galaxies are appropriately corrected for the effect on them of the shifts. Also the necessary adjustments are made for reduction to a simultaneous epoch ; the light received from the galaxies is of varying ages up to hundreds of millions of years during which, if red-shifts are velocity shifts, the galaxies would have receded to appreciably greater and greater distances than those estimated from their apparant faintness.

Some investigators do not agree with Hubble's results. Eddington, for instance, by a different statistical treatment of the counts of galaxies, found that these actually confirm the interpretation of the shifts as an effect of recession. And Shapley does not consider that the evidence for increase in density of distribution outwards, found by Hubble on the hypothesis that the galaxies are receding, is very strong. It is pointed out that if the Mt. Wilson surveys, on which the deduction is based, are employed separately for the two galactic hemispheres, the increase in density in the northern hemisphere is not appreciable ; also that other gradients of changing density of distribution of distant galaxies have been found *across* the sky considerable greater than the radial outwards gradient suggested by Hubble.

It appears sometimes to be assumed that an expanding universe is a necessary consequence of the general theory of relativity. The hypothesis of expansion has certainly got the sanction of that theory ; but this is not by itself a sufficient support as a non-expanding universe can also be fitted into it.

Age of the Universe.

If the galaxies are really receding, then it follows that the radius of the universe doubles every 1,300,000,000 years assuming accelerated velocities, or every 2,000,000,000 years if the velocities are constant. This would mean that about 2000 million years ago all galaxies in the universe were close together and seems to suggest a date for origin of all its stellar and other contents. This extent of time might therefore give an idea of the age of the stars and other celestial objects, while it may be noted that it agrees with the order of magnitude of estimates of the age of the earth and solar system.

Two scales of age for the universe are at present discussed by astronomers—a few thousands of millions, and millions of millions (billions) of years—anything between having little if any evidence to support it. In favour of the shorter scale, which is now tending to take the place of the other, there is the effect of the supposed expansion of the universe already mentioned, and calculations of the probable duration of life of star clusters and of binary stars also appear to favour it.

The duration of life of a cluster of stars as a structure depends on three factors which vary in importance according to the density of the cluster and its position with respect to the centre of the Galaxy. These factors are : gravitational interaction between the constituent stars ; gravitational disturbances by "field" stars passing through or near to the cluster ; and a "tidal" shearing force due to the tendency towards different (and therefore dispersive) velocities, in their galactic orbits, of cluster stars situated at varying distances from the galactic centre, this shearing force being greater for a cluster of a given diameter and constitution the nearer it is to that centre. For loose galactic clusters, like the Hyades or Ursa Major clusters, the first of these factors is not important ; in denser galactic clusters, like the Pleiades or Praesepe, all three are effective ; while for the globular clusters, generally well away from the galectic plane and much more massive, only the first of the three is appreciably important.

The duration of life of the galactic clusters is considered to be of the order of 10^9 to 10^{10} years ; and the simultaneous existence of several hundred of these, estimated to be on their way to what, on the longer cosmic time scale, would be relatively early disintegration, looks more consistent with the shorter time scale than with one which is more than a hundred times as long as their own life times. This assumes that there is no means whereby new clusters are formed which continuously replace those dispersed, an assumption based on the very great improbability of the creation of new clusters by chance encounters between unattached stars, or in any other conceivable way.

For globular clusters, however, the life times are calculated to be much longer—about 10^{12} years. With them the factor of importance, as stated above, is interaction between the constituent stars, which produces "velocities of escape" whereby the stars gradually leave the cluster. It would appear that either the short scale (10^9 to 10^{10} years) or the long one (10^{12} to 10^{13} years) would suit.

As regards binary systems of the wide visual type, their rate of dissolution, and the maximum ages attainable, depend on the nasses and separations of the component stars and also on the star density in their vicinity. For separations of from 1000 to 10,000 times the Earth's distance from the Sun, the maximum ages should range from about 10^{10} to 10^9 years. And statistical enquiry does not show the relatively large number of wider pairs which would result during the much greater periods of time possible with the longer scale.

Further support for the shorter scale may be provided as the result of recent calculations by H. N. Russell, based on the current hypotheses of stellar evolution and the generation of energy by the carbon cycle process, and assuming a composition, for a star in the solar stage, of 51 per cent hydrogen, 42 per cent helium and the remainder the other elements. He gives the times which would be taken, if the universe and its stars existed for so long (a total of about $1{\cdot}6 \times 10^{11}$ years), to pass through the main sequence from K8 through G to B9 spectral types, and shows that because of high absolute magnitudes in the post-Solar stage there would be found, in all surveys down to a given apparent magnitude, at least ten times as many stars in the post-Solar stage as in the Solar and pre-Solar stage, which is of course not the case. Having regard to the fact that the carbon cycle causes a change in mass of only at most 0·7 per cent (see page 81), it may be said that the observed absence of stars of nearly Solar mass but of hotter spectral types and greater luminosities appears to be evidence against the long time scale.

But there is as yet no general agreement. Recent work by Zwicky, for example, on the distribution of the contents and constitution of the clusters of galaxies is taken by him to show that these clusters could not have been formed in the short time of the

smaller scale, and to suggest that the universe is stationary and not expanding at all, and that the red-shift is not produced by motions of recession.

The reader will have noted the uncertainty in such matters as, for example, the source of stellar energy, the origin and evolution of the stars, and in the fundamental question of the red-shifts and their meaning. Much light will be thrown on these by investigations now in progress; in the last-mentioned particularly by the results to be obtained in the next decade or so from the use of the 200-inch telescope at Mt. Palomar. Meantime the aphorism of Lord Bacon (*Advancement of Learning*, v. 8) will be a sound guide for speculation: "If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties."

REFERENCES—PART III—CHAPTER II

Author.	*Publication.*	*Subject.*
E. Hubble,	"The Realm of the Nebulae."	Galaxies and the Universe.
E. Hubble,	"The Observational Approach to Cosmogony."	Ditto.
H. Shapley,	"Galaxies,"	Ditto.
H. Shapley,	*Harvard College Observatory Bulletin*, No. 864.	Transparency of Space.
A. S. Eddington, J. Jeans, E. A. Milne.	*Observatory*, **58**, 108.	Discussion on Age of Universe.
B. J. Bok,	*Observatory*, **59**, 77.	"Galactic Dynamics and the Cosmic Time-scale."
F. Zwicky,	*Pub. Ast. Soc. Pac.*, **54**, 185.	"Clusters of Nebulae."
B. J. Bok,	*Monthly Notices Royal Astronomical Society*, **106**, 61.	"The Time-Scale of the Universe."

APPENDIX A.

Explanation and Derivation of some Astrophysical Terms.

Absolute Magnitude—The formula for this is

$$M = m + 5 + 5 \log \pi$$

where M is absolute magnitude, m stellar magnitude (visual, photographic or bolometric) and π parallax in seconds of arc. This expression is derived as follows :—The ratio of apparent brightness at distances corresponding to a parallax π and to one of $0''\cdot100$ is $2{\cdot}512^{m-M}$ This ratio is also $\left(\frac{0{\cdot}100}{\pi}\right)^2$ since light received varies inversely as the square of the distance or directly as the square of the parallax. Hence

$$2{\cdot}512^{m-M} = \left(\frac{0{\cdot}100}{\pi}\right)^2 \text{ from which}$$

$$(m - M) \log 2{\cdot}512 = -2{\cdot}0 - 2 \log \pi$$
$$M = m + 5 + 5 \log \pi, \text{ since } \log 2{\cdot}512 = 0{\cdot}400,$$
$$\text{Or } M = m + 5 - 5 \log r \ (r \text{ in parsecs}) ; \ M = m + 7{\cdot}56 - 5 \log d$$
$$(d \text{ in light years}).$$

Bolometric Magnitude, Effective Temperature and Surface Brightness—Total radiation varies as surface area and also as the fourth power of effective temperature (Stephan's Law). It consequently is $= D^2T^4 \times$ a constant. In order to define bolometric stellar magnitude it is necessary to adopt some standard and this is done by assuming $\frac{\text{luminosity}}{\text{total radiation}}$ $=1$ in the case of a star of effective temperature about 6000°K. As the Sun has almost this temperature (5800°K.), we may use its absolute magnitude to derive an approximate formula for bolometric absolute magnitude as follows :—

$$M_{\text{bol}} = 4{\cdot}9 - \frac{2 \log D}{\log 2{\cdot}512} - \frac{4 \log (T/5800)}{\log 2{\cdot}512}$$
$$= 4{\cdot}9 - 5 \log D - 10 \log (T/5800) \quad (1)$$

Similarly total luminosity, or visible radiation, is $= D^2 j \times$ a constant, when j is the surface brightness per unit of area of a star compared with the Sun. Visual absolute magnitude is then

$$M_{\text{vis}} = 4{\cdot}9 - 5 \log D + J \quad (2)$$

J being the difference between the star's and the Sun's surface brightness in stellar magnitudes. The correction to visual absolute magnitude (or to visual apparent stellar magnitude) in order to obtain bolometric magnitude is, by subtraction of (1) from (2) :—

$$M_{\text{vis}} - M_{\text{bol}} = 10 \log (T/5800) + J.$$

The values of T have been found for different types by several independent methods, while J has been ascertained from studies of eclipsing binaries, differences of colour index, and interferometer measurements of stellar diameter. In the Table, approximate figures for various classes of stars are given for T, J and $(M_{\text{vis}} - M_{\text{bol}})$:—

Giants.			
Spectrum.	T	J	$M_{\text{vis}} - M_{\text{bol}}$ ($m_{\text{vis}} - m_{\text{bol}}$)
B0	20,000°K	− 3·2	+ 2·2
A0	10,500	− 2·3	+ 0·3
F0	7,400	− 1·0	+ 0·1
G0	5,200	+ 0·3	+ 0·1
K0	4,000	+ 2·3	+ 0·7
M	3,100	+ 4·5	+ 1·8

Main Sequence.			
Spectrum.	T	J	$M_{\text{vis}} - M_{\text{bol}}$ ($m_{\text{vis}} - m_{\text{bol}}$)
B0	20,000°K	− 3·2	+ 2·2
A0	10,500	− 2·3	+ 0·3
F0	7,400	− 1·0	+ 0·1
G0	5,800	0·0	0·0
K0	4,700	+ 1·2	+ 0·4
M	3,300	+ 3·8	+ 1·6

Colour Index (*photographic mag.* minus *visual mag.*)—This has been determined by Seares for different types, as follows :—

Spectrum.	*Giants.*	*Dwarfs.*
B0	− 0·32	− 0·32
A0	0·0	0·0
F0	+ 0·38	+ 0·38
G0	+ 0·86	+ 0·72
K0	+ 1·48	+ 0·99
M	+ 1·88	+ 1·76

According to this table, the dwarf stars of G, K and M type are not so "red" as the giants of the same spectral type, *i.e.*, they have a higher effective temperature, which is also shown in the preceding table of temperatures, etc.

Colour index was at first obtained exclusively by comparison between photographic and visual, or photo-visual, magnitudes. It is now more usually determined by the photo-electric cell from measurement of galvanometer or electro-meter deflections when the star's light is passed through colour filters. This method is susceptible of considerably greater accuracy, giving results believed to be within one per cent of the correct value.

Space Reddening.—Distant stars are often noted to be redder, *i.e.*, have a greater colour index than what is appropriate to their spectral type. The difference between the observed colour index and the normal value is termed the colour excess. It has been found to be greatest in directions towards the galactic centre and low galactic latitudes. Several investigators have measured it to average about a tenth of a magnitude per 1000 light years distance. But it may be noted that abnormal reddening will not be always entirely due to interstellar matter, some effect of the kind being observed in the case of stars with emission lines in their spectra.

APPENDIX B.

Spectral Characteristics.

O Type—There are two groups: one shows bright bands due to hydrogen, helium and some other elements, and the other shows absorption lines of the same substances. The first group are the "Wolf-Rayet" type, the second are the "absorption–O" type (Examples—γ Velorum, ι Orionis)."

B Type—Absorption lines of helium and hydrogen most prominent (δ Orionis).

A Type—Hydrogen lines most prominent (Sirius).

F Type—Calcium H and K lines most prominent with hydrogen lines next (δ Aquilae).

G Type—H and K lines; but hydrogen lines no longer prominent; many metallic lines (Sun).

K Type—Calcium still strong; numerous metallic lines and continuous spectrum decreasing rapidly towards violet (Arcturus).

M Type—Calcium still prominent, with bands in green, and blue and violet end very weak (Betelgeuse). M_a, M_b, M_c are now referred to as M0, M3, M8 respectively.

R and N Types seem to constitute a sort of side chain branching off at G or K; R and N taking the place of K and M in the order, while *S type* represents a similar third branch. S is characterised by absorption bands of zirconium oxide; R and N by bands due to carbon compounds.

The spectra of the bright-line gaseous nebulae are classified as *P*; temporary stars as *Q*. The letter *g* and *d* prefixed to the type letter signify giant or dwarf respectively; *e* attached indicate the presence of bright lines, *p* that the spectrum is peculiar.

APPENDIX C.

Stellar Temperature and Distribution of Energy in Spectra.

The total radiation from a perfect radiator follows Stephan's Law, which states that the total energy in all wave lengths radiated per second from each square centimetre of a hot black surface is

$$E = \sigma T^4$$

σ is a constant determined experimentally as $5{\cdot}72 \times 10^{-5}$ and T is absolute temperature in degrees centigrade. The value of E for the Sun is $6{\cdot}25 \times 10^{10}$ ergs per second per square centimetre as determined experimentally by Abbott and others (10,000,000 ergs per second is a watt or $\frac{1}{746}$ of one horse-power). From the formula T is found to be 5750°K. The temperature can also be found from Wien's Law, which states that the maximum intensity of radiation in a perfect radiator is

$$\lambda_m = \frac{0{\cdot}289}{T} \text{ centimeters.}$$

By studies of the Sun's spectrum with a bolometer λ^m is found to be $4{\cdot}70 \times 10^{-5}$ centimetres, giving $T = 6150$°K. Stellar temperatures can be similarly ascertained.

For the hotter stars (20,000°K), $\lambda^m = 1{\cdot}45 \times 10^{-5}$ cms.; for the coolest (2000°K) it is $1{\cdot}45 \times 10^{-4}$ cms. This means that to obtain an adequate knowledge of stellar spectra a considerable range of wavelength has to be photographed. Assuming that all points in the spectra where the energy exceeds 10 per cent. of that at maximum must be covered to achieve this, the range to be photographed is from 6×10^{-6} to 5×10^{-4} cms., which becomes in effect $2{\cdot}9 \times 10^{-5}$ at the shorter end owing to absorption by ozone in the earth's upper atmosphere.

APPENDIX D.

Modern Indirect Methods of Parallax Estimation.

Some of the principal indirect methods are described briefly below :—

Spectroscopic Parallaxes—These are due to the discovery by W. H. Adams and Kohlschutter that the intensity of certain lines in stellar spectra varies with the luminosity of the star. For example, in the two K type stars, Aldebaran (giant) and 61 Cygni (dwarf), the lines at λ 4077 and λ 4215 (both due to strontium) are strong in Aldebaran and weak in 61 Cygni, the reverse being the case for the calcium line λ 4227. By calibration of such relationships in stars for which parallax and absolute magnitudes have been directly obtained, it is found possible to determine a definite numerical relationship between absolute magnitude and intensity of lines. Thousands of parallaxes of stars down to 8th magnitude and fainter have been thus obtained. Theory shows that these variations of line intensity are due to the state of "ionisation" of atoms in a stellar atmosphere, and are connected with the gravity potential at the star's surface. Spectroscopic parallaxes are therefore correct only for stars of mass equal to the average of their type corresponding to those used in making the calibration curves, and seem to require some mass-factor correction, stars of large mass giving too large spectroscopic parallaxes and *vice versa*.*

Spectral Parallax is obtained by assuming the absolute magnitude to be equal to the mean for the spectral type. For example, Vega is an A0 star of 0·1 apparent visual magnitude. Assuming that it is a "main sequence" star of average luminosity, the absolute magnitude is +0·6 (see Table 3). From the formula $M = m + 5 + 5 \log \pi$ (Appendix A) we get $5 \log \pi = M - m - 5$, whence spectral parallax of Vega is 0″·126, which is very nearly the same as the best trigonometrical values. Usually it is not possible to say whether a star is a giant or a dwarf without careful examination of the spectrum. Proper motion is a fairly good criterion, a large value usually indicating a dwarf star. In the case of double stars, the relationship of spectra (see page 46) gives a good indication, and spectral parallaxes for double stars are of some value. In clusters of physically connected stars the magnitudes and spectra when plotted often show a configuration resembling that of Fig. 1. The absolute magnitudes of the stars can thus be derived and an approximate parallax for the cluster obtained.

Variable Star Parallaxes—One of the most powerful aids to the estimation of great distances has been provided by the Cepheid period-luminosity relationship (see Table 16). An example will illustrate. A faint variable star with a light curve showing Cepheid characteristics, a period of 20 days and median photographic magnitude 19·0, is found on photos of a spiral nebula taken with a powerful reflector: what is the distance? The absolute magnitude (Table 16) is −2·6; from the formula $5 \log \pi = M - m - 5$ we get a parallax of about 0″·0000048, corresponding to a distance of about 700,000 light years. This illustrates the method, but a number of Cepheids in such an object would be thought necessary for a reliable determination. The Long Period variable stars may also be used to find distances approximately, using an absolute magnitude according to period. (See p. 52).

* Despite the rather despondent outlook of R. A. Proctor, referred to on page 1, he made a very interesting speculation a few years later (*Mysteries of Time and Space*, p. 410, 1883). This was to the effect that the various degrees of strength of the lines in stellar spectra might provide evidence as to the size of a star, and that "if so, se shall have a new means of dealing with the architecture of the heavens; for, knowing something of the real size of a star in this way, we may infer its distance from its apparent size, and thus place it correctly in position in space, instead of knowing only the direction in which it lies." (By "size" Proctor, of course, here means brightness). A similar suggestion, made later by Schwarzschild, was recollected by Kohlschutter and acted upon by him and Adams in 1914.

Dynamical Parallaxes of Double Stars—By adopting a total mass for a binary system for which the orbital elements are known, it is possible to derive a parallax from a formula based on Kepler's Laws,

$$\text{parallax} = \frac{a}{(m_1 + m_2)^{\frac{1}{3}}\, P^{\frac{2}{3}}}$$

where a is the semi-axis major of the orbit in seconds of arc, $m_1 + m_2$ the combined mass (usually assumed to be about twice that of the Sun) and P the period in years. Rather accurate approximations to parallax can be obtained by using in conjunction with this formula the empirical mass-luminosity formula (page 11). For example, taking the binary Σ 3121, magnitudes 7·3, 7·6, $P = 34$ years, a 6″·8, and assuming $m_1 + m_2 = 0·5$, 1·0, 2·0 and 3·0, we get :—

Assumed $m_1 + m_2$,	0·5	1·0	2·0	3·0
Parallax (from formula above)	0″·081	0″·064	0″·051	0″·045
Corresponding abs. mags.	6·8, 7·1	6·3, 6·6	5·8, 6·1	5·6, 5·9
Combined masses by mass-luminosity formula,	1·3	1·45	1·6	1·7

On plotting the mass values of the first and fourth lines against the parallaxes of the second line, two curves are obtained which intersect at a parallax of 0″·056, identical with the best trigonometrical result. The value of this method may be considerable in the case of remote pairs, where the errors of observation are of the same order as the parallaxes themselves (see *Observatory*, April, 1925, p. 113).

In the case of slow-moving pairs, for which the elements of an orbit are not known, an approximation of some value for parallax can be obtained. Taking the simplest case of a pair with a circular orbit, the plane being at right angles to the line of sight, we get $P = 6·28\, a/v$, where 6·28 is the ratio of circumference to radius of a circle, and v the rate of relative motion of the components. Substituting for P in the formula,

$$m_1 + m_2 = \frac{a^3}{P^2\, \pi^3} \text{ we get}$$

$$\pi^3 = \frac{a\, v^2}{39·7\, (m_1 + m_2)},\ \pi = 0·29 \sqrt[3]{\frac{a\, v^2}{m_1 + m_2}}$$

This formula can be adjusted by the theory of probability for ellipticity and foreshortening of orbit, and then becomes for the average case (using 2·0 for $m_1 + m_2$) —

$$\pi = 0·33 \sqrt[3]{s\, w^2}$$

where s is the apparent angular separation and w the apparent mean annual relative motion, both in seconds of arc. Appropriate values for $m_1 + m_2$ can be adopted to suit the particular case. There are also other similar formulae of some utility, particularly in statistical work. One of these is

$$\pi = 0{\cdot}022 \; s \; \theta^{\frac{2}{3}}$$

where s is the mean angular separation and θ the mean annual change in position angle of the components.

Eclipsing Binaries—By the study of the light curve and radial velocity curve, the absolute sizes of eclipsing pairs can be ascertained. The spectral type being known, the absolute magnitude can be calculated from the surface brightness. For example, on page 44, it is explained how the diameter of the brighter star in the Algol system, spectrum B8, has been found to be 3·1 (Sun = 1). If of G0 type the luminosity would be $3{\cdot}1^2$ or 9·6 times the Sun, or nearly 2·5 magnitudes brighter. The surface brightness J for a B8 star being $-2{\cdot}5$ (see Table, Appendix A), it follows that the absolute magnitude of the primary of Algol is $M = 4{\cdot}9 - 2{\cdot}5 - 2{\cdot}5 = -0.1$. The apparent magnitude is 2·1 and the parallax (from $5 \log \pi = M - m - 5$) is 0″·036, which is fairly close to the trigonometrical result (0″·027). Corroboration is afforded by the mass of the star, 4·7 times that of the Sun, which corresponds (by the mass-luminosity formula) to an absolute magnitude of $-0{\cdot}4$ and a parallax of 0″·032. The parallax of Algol is therefore probably very close to 0″·032, the mean of the three values.

APPENDIX E.

Apparent Angular Diameters of the Stars.

These can be estimated if visual magnitude and spectral type are known. If j is the surface brightness compared with that of the Sun, then, taking 1919″·3 as the Sun's mean angular diameter and $-26{\cdot}7$ as its apparent stellar magnitude, D″ being the angular diameter of the star, we have—

$$\frac{\text{Light from Sun}}{\text{Light from Star}} = 2{\cdot}512^{m+26\cdot7}$$

$$\text{or} \quad \left(\frac{1919{\cdot}3}{D}\right)^2 \frac{1}{j} = 2{\cdot}512^{m+26\cdot7}$$

$$\text{and} \quad D'' = 0{\cdot}0088 \; j^{-\frac{1}{2}} \; (0{\cdot}631)^m$$

For example, the calculated angular diameter of Arcturus, $m = 0{\cdot}2$, spectrum K0, $J = +\,2{\cdot}3$ (whence $j = 0{\cdot}12$) is

$$0{\cdot}0088 \times 2{\cdot}9 \times (0{\cdot}631)^{0\cdot2} = 0''{\cdot}023$$

which is nearly the same as found by interferometer measurement at Mt. Wilson (see Table 1).

Actual Diameters—The luminosity of a star, compared with that of the Sun, is proportional to the squares of their diameters multiplied by their surface brightnesses. In terms of stellar magnitude :

$$M = \text{Sun's abs. mag.} - \left(\frac{2 \log D}{\log 2{\cdot}512}\right) + J$$

$$= 4{\cdot}9 - 5 \log D + J$$

whence

$$\log D = 0{\cdot}2\,(J + 4{\cdot}9 - M),$$

M being absolute magnitude, and D the diameter of the star (Sun = 1).

APPENDIX F.

Average Distance of Stars to Nearest Neighbours.

It may be shown (see *B.A.A. Journal*, **36**, 31) that the average distance from a star to its nearest neighbours is given by the expression

$$s = 1{\cdot}61 \frac{r}{N^{\frac{1}{3}}}$$

where s = distance required, r = radius of volume considered and N number of stars in that volume. The most recent work indicates that there is about one star per 300 cubic light years in the Sun's vicinity, which is the same as one star per sphere of 4.15 light year radius, whence

$s = 1{\cdot}61 \times 4{\cdot}15$ light years,
or about 7 light years.

APPENDIX G.

Density of Interstellar Matter in the Galaxy.

Assuming that the total interstellar mass (gas and dust clouds) is equal to 10^{11} times that of the Sun ; diameter (central lenticular part), 100,000 light years, thickness (maximum), 20,000 light years, we have

Mass of Sun $= 1{\cdot}98 \times 10^{33}$ grammes.
Total Mass $= 1{\cdot}98 \times 10^{33} \times 10^{11} = 1{\cdot}98 \times 10^{44}$ gms.

$$\text{Total Volume} = \frac{\pi}{6} \; \frac{\text{Diameter}^3}{5} \; (\pi = 3{\cdot}14 \; . \; . \; . \; . \; .).$$

$$= 1{\cdot}05 \times 10^{-1} \; (10^5 \times 9{\cdot}46 \times 10^{17})^3 \text{ cm.}^3$$

$$= 8{\cdot}6 \times 10^{68} \text{ cm.}^3$$

$$\text{Density} = \frac{1{\cdot}98 \times 10^{44}}{8{\cdot}46 \times 10^{68}} = 2 \times 10^{-25} \text{ gm./cm.}^3$$

That is to say, of the order of 10^{-25} that of water, as against the 10^{-22} required in the hypothesis of collection of hydrogen mentioned on page 87.

APPENDIX H.

Approaches and Collisions between Stars.

Assuming that the stars are scattered at random, the expression for the time between approaches of stars in general to a given star is

$$t = \frac{S}{3{\cdot}14\ l^2\ v}$$

where t is in years, S is the volume containing one star, l the limiting distance and v the average relative velocity of the stars.

Let S = 300 cubic light years, l = the radius of Neptune's orbit ($\frac{1}{2150}$ light year) and v = 25 miles per second ($\frac{1}{7400}$ light year per year), then

$$t = \frac{300 \times 2150^2 \times 7400}{3{\cdot}14}$$

$$= 3{\cdot}2 \times 10^{12} \text{ years,}$$

i.e., there would be, on the average, one approach within a distance equal to the radius of Neptune's orbit every 3 billion years.

It can be shown that for actual collision, allowing for the effect of mutual gravitational attraction, something like one hundred thousand billion years (10^{17} years) would be necessary, and that with 35 thousand million stars (the number suggested by Seares and van Rhijn) there would be a direct collision observed only about once every three million years; The number of dark bodies necessary to account for novae on a collision, or even near approach theory (although near approaches are much more numerous than collisions) seems too great.

APPENDIX J.

Apparent Magnitudes and Distances of Galaxies.

The formula $M = m + 5 + 5 \log \pi$ may be written

$M = m + 5 - 5 \log r$, where r is distance in parsecs.

From this $\log r = \dfrac{m + 5 - M}{5} = 0{\cdot}2 + 1 - \dfrac{M}{5}$

Substituting -15 for M, we get

$$\log r = 0{\cdot}2m + 4{\cdot}0$$

$$\text{or } \log d = 0{\cdot}2m + 5{\cdot}51$$

when d is in light years instead of parsecs.

The value -15 is for an average galaxy. As the limiting magnitude photographed by the Mt. Wilson, 100-inch is 21, such a galaxy would be at a distance so that $\log d = 0{\cdot}2 \times 21 + 4{\cdot}51 = 8{\cdot}71$, which corresponds to a distance of 500 million light years.

APPENDIX K.

The Cepheid Period-Luminosity Relation.

A theoretical period-luminosity relation can be derived which gives some support to the values of the accepted curve; or, alternatively, gives support to the application of the relation to galactic Cepheids where it has not yet been possible to derive it directly owing to the very small parallaxes and proper motions involved.

The relation period (P), inversely proportional to the square root of the density (ρ), may be written as P^2 proportional to $1/\rho$. Volume is proportional to mass/density (μ/ρ), and the surfaces of the stars are proportional to the two-thirds power of the volume, or to $(\mu/\rho)^{\frac{2}{3}}$. Assuming the period-luminosity relation to be valid P^2 can be substituted for $1/\rho$, and we have surface proportional to $(\mu\ P^2)^{\frac{2}{3}}$. As radiation is proportional to surface and to the fourth power of the surface temperature (Stephan's Law) we have—

Radiation $(R) = \text{k}\ (\mu\ P^2)^{\frac{2}{3}}\ T^4$, where k is a constant,

whence $\text{k} = R/\mu^{\frac{2}{3}}\ P^{\frac{4}{3}}\ T^4$.

From this formula, absolute bolometric magnitudes may be derived, estimating masses by a curve based on the formula of page 11, and assuming $-3{\cdot}2$ (the observed value for the 10-day Cepheid).

Period days.	*Mean Spectrum.*	*Effective Temperature.*	*Bolometric abs. mag. (Observed)*	*Estimated Mass (Sun = 1)*	*Bolometric abs. mag. (Computed).*
0·5	A 6	8500°	−0·4	3·7	−0·5
1·0	F 1	7100°	−0·9	4·4	−0·9
5·0	G 1	5100°	−2·5	8·4	−2·3
10·0	G 3	4750°	−3·2	12·0	(−3·2)
20·0	G 6	4400°	−4·1	19·5	−4·2
50·0	G 9	4100°	−5·6	45	−5·7

The agreement between the observed and calculated values of bolometric magnitude provides remarkable support for the relative accuracy of the period-luminosity curve; and at the same time for the validity of the theoretical relation between period and density in Cepheids, the computed magnitudes being based entirely on observational data, astronomical or laboratory, *plus* the assumption of the gravitational period-density relationship referred to.

It is also worth noting that calculation on the same lines, but adopting a brighter or fainter absolute magnitude than −3·2 for the 10-day Cepheid, shows larger differences for the stars of shorter or longer periods than in the table above. This is at least a rough confirmation of the *order* of luminosities of the accepted period-luminosity curve, the general trend of which is shown to be very close to what is calculated from the assumptions in the table. (See *B.A.A. Journal*, **38**, 255, 1928).

APPENDIX L.

The Mean Distance of a Galaxy to its Nearest Neighbours.

From the formula—

$$\text{Log } d = 0{\cdot}2\,m + 4{\cdot}51,$$

the distance of an average galaxy, and the effective limit for the 100 million galaxies, which can be photographed with the 100-inch reflector, is 500 million light years (Appendix J).

By the formula in Appendix F,

$$s = 1{\cdot}61\ \frac{r}{N^{\frac{1}{3}}}\quad \text{(where } s \text{ is distance apart)},$$

we get as the average distance to its nearest neighbour,

$$s = 1{\cdot}61\ \frac{500{,}000{,}000}{100{,}000{,}000^{\frac{1}{3}}} = 1{,}730{,}000 \text{ light years.}$$

APPENDIX M.

Hypothesis of Cosmic Evolution.

There are so many uncertain factors, such as the question of the expanding or stationary universe, its size, the density of the matter in it (masses of galaxies being still uncertain), the real nature of the spiral arms, etc., that it has been thought advisable to condense the account of the speculations of Sir James Jeans, given at some length in the first edition of this book, into this appendix, as an interesting and valuable hypothesis, but hardly more than that at present.

Jeans draws attention to the great numbers of external nebulae of regular shapes (elliptical, spiral, etc.), each in mass and size apparently a star system. Differing in shape and in apparent dimensions and brightness, those of the same type are mostly of the same real size and roughly the same luminosity. The types can be arranged in a practically continuous sequence which, he considers, it is reasonable to believe is an evolutionary one.

Rotating initial spheres of gaseous matter were formed from the original chaos ; these can be calculated, on reasonable asumptions of the density and temperature of the primeval medium, to have had the mass of an average external galaxy, and also to have had the spacing apart which is observed. The effect of tidal forces caused on each other, no matter how small, can be shown to be ejection of matter localized at two opposite points on the equatorial edge of the flattened rotating spheroids, taking the form of spiral streams, in which condensations would form, the mass and spacing of which can again be estimated, on reasonable assumptions of density and temperature, to be what should be expected for the stars as we find them.

Thus Jeans considers that at one stroke there is a possible explanation of the formation of the stellar contents of the universe.

The scheme outlined deals with three generations of astronomical bodies as follows :—

First, a primeval chaos of hundreds of millions of light years diameter (or less if the universe is expanding) and a total mass of the order of at least 10^{15} times that of the Sun ; second, a series of stellar systems of the galactic type thousands of light years in diameter and of masses of the order of 10^{9} times the Sun's ; third, stellar bodies of solar mass, each generation having been derived from the preceding, chiefly through the agency of "gravitational instability."

It may be observed of this hypothesis that if the spiral arms "trail" behind the nucleus in its rotation (*i.e.*, move with their convex sides in front), which appears to be probably the case (see page 129) formation by ejection as described could not have taken place. It may also be remarked that the difficulties attending an explanation of the origin of rotational movement of the condensations are not met.

GLOSSARY

(Of Some Important Terms)

Angular Diameter, Apparent: the angular separation between lines of sight to diametrically opposite points in the apparent outline or disc of an object.

Atom: the smallest amount of an element which can enter into a chemical reaction; it consists of a *nucleus*, in which is concentrated most of the mass, made up of at least two kinds of particle, positively charged *protons* and neutral *neutrons*, each with a mass nearly equal to that of a hydrogen atom. The number of protons in the nucleus equals the number of surrounding *electrons* (each of mass nearly equal to 1/1840 of a hydrogen atom), the total of the negative charges on which balance the total positive charges on the nuclear protons. This number is the *atomic number* of the element. The *atomic weight* is very nearly equal to the number of protons and neutrons together. Other particles possibly concerned in atomic structure are the *positron* and the *neutrino*, each with the same mass as the electron, but with a positive charge and no charge respectively, and the *mesotron* with the same charge as an electron, but about 150 times as great a mass.

Bolometer: an instrument for measuring heat radiations, used with large telescope for the study of the radiation from, and temperatures of, stars and planets. It consists of two very thin strips of blackened platinum forming two arms of an electrical circuit, the increase in resistance due to the radiation absorbed being measured by a galvanometer.

Catalyst: a substance which, while accelerating (or retarding) the speed of a chemical reaction, suffers no perceptible change; it probably acts by the formation of some reactive intermediate compound.

Cosmogony: theories on the origin and evolution of celestial bodies.

Cosmology: the science concerning such theories.

Deuterium: "heavy" hydrogen, an isotope (*q.v.*) of that element of atomic weight 2·014. Deuteron: the nucleus of a deuterium atom, composed of a positron and two neutrons, or of a proton and a neutron; possibly concerned with production of energy in the interior of a star at an early evolutionary stage.

Doppler's Principle alteration in frequency of light vibrations due to motion of a source towards or away from an observer, whereby a receding body appears redder and lines in its spectrum are displaced towards the red, or bluer and towards the blue in the case of an approaching body.

Galaxies: nebulae observed outside the Galaxy (Milky Way system); gigantic clusters of stars or "island universes" separated from one another by enormous distances.

Galaxy, The our own stellar system, composed of stars, dust and gas and radiation.

Ionisation: the subtraction from (positive ionisation) or addition to (negative ionisation) an atom or molecule, of electrons; it results in alterations in the lines of the spectrum, atoms which have lost two, three or more electrons having spectra built on the same plan as those of elements of an atomic number less by the number of lost electrons.

Isotopes: varieties of an element of the same properties and atomic number, but different atomic weights, the atomic nuclei being of different structure and different numbers of contained neutrons.

Light Year: the distance travelled by light in one year, 63,290 times the radius of the Earth's orbit (*Astronomical Unit*), or $5{\cdot}88 \times 10^{12}$ miles, or 0·307 parsecs (*q.v.*).

Luminosity: the total actual output of a star, as opposed to its apparent brightness in the sky or, also, to its surface brightness per unit of radiating area. It is usually measured with the Sun's value as the unit.

Magnitude, Stellar: a star's brightness as compared with an adopted standard such as the Pole star, or with a sequence of stars based on the Pole star. It is graded so that a star of a given magnitude is 2·512 times brighter than one of the next lower magnitude; this figure corresponds to an assumed ratio of 100 for a difference of five magnitudes.

Nuclear Charge: the net positive electric charge on the nucleus of an atom, numerically equal to the atomic number, to the number of protons in the nucleus, and to the number of electrons outside of the nucleus.

Parallax, Stellar: the angular change in position of a star in the sky caused by the movement of the earth round the Sun. It is expressed as the angle subtended by the radius of the earth's orbit as it would be seen from the star. *Trigonometric parallax* is obtained in modern methods by photographic measurements of the displacements relative to fainter background "comparison" stars, corrections being applied for the estimated smaller parallactic displacements of these stars (*i.e.*, a correction from relative to absolute parallax).

PARSEC: the distance corresponding to a stellar parallax of one second of arc, equal to 3·26 light years (*q.v.*) or to 206,265 astronomical units, or to $19{\cdot}16 \times 10^{12}$ miles.

PHOTON: a quantum (*q.v.*) of radiant energy, the fundamental unit of light intensity.

PHOTOSPHERE: the luminous surface of a star, from which much the greatest part of its radiation proceeds; situated at about the level where the atmospheric and ejected parts of the star's material begin.

PROPER MOTION the apparent angular motion (per year or per century) of a star or other celestial object outside the solar system, on the celestial sphere.

QUANTUM: fundamental unit of radiation with which is associated a definite amount of energy which is dependent only on the frequency of the radiation.

RADIAL VELOCITY: the motion per second in the line of sight of a star or other celestial object as ascertained by the application of Doppler's Principle (*q.v.*).

RADIATION: the emission of any rays, wave motion or electrically charged particles, from a source. The term is usually applied to electromagnetic waves travelling at 186,300 miles per second; the best known, in order of increasing wave length, are gamma rays, X-rays, ultra-violet rays, visible light rays, infra-red (heat) rays, wireless or Hertzian waves.

RADIATION PRESSURE: pressure on a surface due to the momentum which (as well as energy) is carried by electromagnetic waves. It is of importance in its effects on interstellar matter, and in the interior of a star where it is extremely intense.

TEMPERATURE, ABSOLUTE: temperature on the absolute or Kelvin scale, zero being taken as the temperature at which the molecules of a gas would have no kinetic energy, *i.e.*, at −273°C.; absolute temperature is thus temperature in degrees centigrade, *plus* 273.

WAVE-LENGTH: the distance between corresponding phases, *e.g.*, from crest to crest, of two consecutive waves. It is usually expressed in Angström units of 10^{-8} cm. or $0{\cdot}39 \times 10^{-8}$ inch, and denoted by the prefix λ. Thus λ 6000 refers to a wave-length of 6×10^{-5} cm. or 1/42,330 inch. The unit micron (μ) is sometimes used; it is 10,000 Angströms, 10^{-4} cm., or $0{\cdot}39 \times 10^{-4}$ inch.

INDEX

Printed by Milne, Tannahill & Methven, Ltd., 12-14 Mill Street, Perth, Scotland.

AN
OUTLINE
OF
STELLAR
ASTRONOMY

•

PETER
DOIG,
F.R.A.S.

HUTCHINSON'S
SCIENTIFIC