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THE O-TYPE STARS AND THEIR RELATION TO THE STELLAR EVOLUTIONARY SEQUENCE*

By J. S. PLASKETT

INTRODUCTION

The choice of the above subject for the presidential address to Section III of the Royal Society was governed by two main reasons. First an investigation of the radial velocities and other phenomena of all the O-type stars within reach at Victoria has occupied most of my time for the past three years, the results are now in press, and it seemed useful to present here a summary of the most important conclusions reached and their bearing on present day ideas of the course of stellar evolution. Second the subject is sufficiently comprehensive to include all the sciences represented in Section III for as we shall see, mathematics, physics and chemistry have been required to an almost equal degree with astronomy in the development of the accepted theory of stellar evolution.

The astronomical material available for attacking this problem is relatively meagre and incomplete. The scantiness of our information about the stars is due to their enormous numbers, the feebleness of their light, the minuteness of their apparent motions, and their almost inconceivable distances. Hence there is available only partial and scattered knowledge about two or three thousand of the brightest from among a thousand million stars and even then

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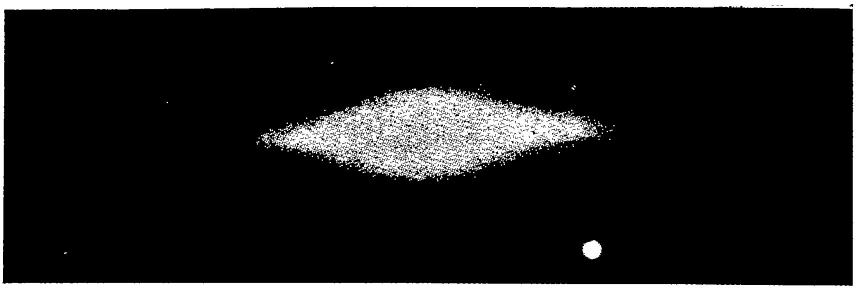
*This paper is an amplification of the presidential address to Section III of the Royal Society of Canada given at Quebec, May 21, 1924.



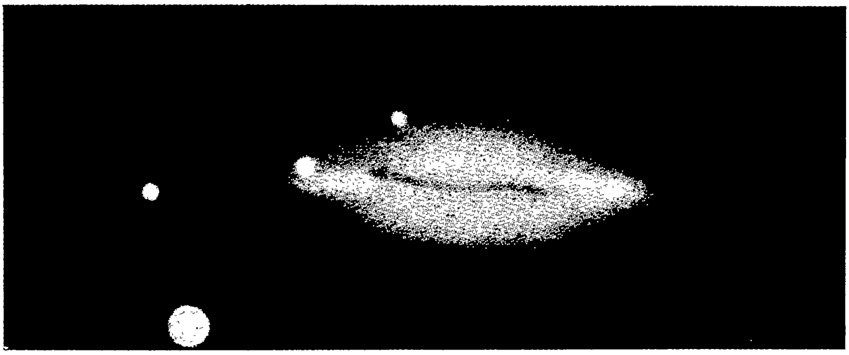


PLATE X

Figures 3, (top), 4, 5, 6 (bottom)

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the obvious limitations of distance, size and temperature make any detailed examination, such as is possible in laboratory investigations, entirely out of the question. The attainment of additional astronomical data is such a slow and laborious process that were it not for the aid of the sister sciences to fill in the unavoidable gaps, the problem would have been almost hopeless of solution. That such a beautiful and apparently complete theory, which I shall now attempt briefly to sketch and show the peculiar place of the O-type stars therein, has been developed is a tribute to the resourcefulness and ingenuity of the human mind.

Evolution of the Nebulae

Without further preface, therefore, let us proceed to outline the probable course of development of the stellar universe. In all sciences it is necessary to start with some original postulates or primal substance, and in astronomy it is necessary to assume the existence of enormous quantities of matter of unknown origin, widely scattered over space in vast clouds of finely divided and probably ultimately gaseous material of almost inconceivable tenuity. These clouds by internal gravitational action would slowly aggregate into approximately globular form and any initial rotation, produced by initial motions or irregular distribution would inevitably increase on condensation, by reason of the conservation of angular momentum. The physical and mathematical treatment of the subsequent development, we owe to the genius of Jeans, who has given us a beautiful picture of the probable evolution of these enormous globes of gas or meteoric dust of density about one million billionth of our atmosphere and yet containing sufficient material to produce thousands or prehaps millions of suns.

Jeans' mathematical treatment of the subsequent process has shown that the increasing rotational velocity resulting from condensation would first produce a spheroidal form. However, in such a highly compressible nebula, the equatorial bulge even for moderate rotations becomes more pronounced and at a certain critical speed develops a sharp edge as shown in Figs. 1 and 2. Further increase of speed consequent upon continuing contraction cannot be compensated by any further adjustment of figure and the resultant of the action of the centrifugal forces, the molecular interactions or viscosity, and the increasing angular velocity of the inner part will cause an outer ring of matter to appear to be thrown off, expanding as it rotates.

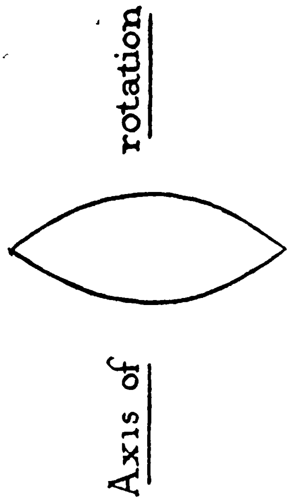

Fig. 1

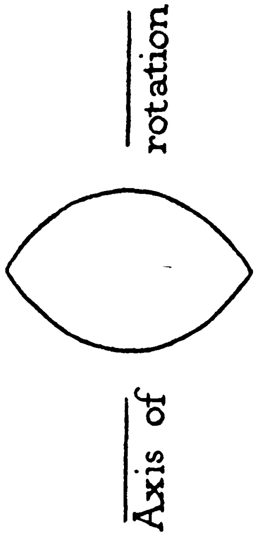

Fig. 2

Mathematical analysis here becomes uncertain, but fortunately we can supplement it by observation and show nebulae actually photographed, apparently illustrating successive steps in the process of evolution. Figs. 3 to 6 (Plate X) show photographs of nebulae as arranged by Jeans in probable order of development. Fig. 3 is an observed example of the lenticular forms mathematically developed in Figs. 1 and 2. Fig. 4 shows an example which may represent, by the bright and dark equatorial appearances, the throwing off of a ring of matter. This is confirmed by Fig. 5 in which the emitted ring has cooled down and is obscuring the light of the nucleus. This nebula has been spectroscopically shown to be in relatively rapid rotation thus further confirming the theory. Finally there can be no doubt that Fig. 6 is a photograph of the familiar spiral nebula seen edge on, thus completing the chain of development.

The expanding ring of gaseous matter is unstable, cannot remain continuous and breaks up into condensations. Very few examples of such concentric rings of condensation are known, the most conspicuous example being N.G.C. 7217, while in the overwhelming majority the condensations lie along two spiral curves, appearing to branch out from opposite sides of the central nucleus. Although there are many difficulties in the mathematical treatment, the concentric rings seem to correspond to the ideal case where the nebula is isolated in space, while the spiral form results from the tidal action of neighbouring nebulae. Such tidal action, whether small or great, will tend to localize the ejection of matter to two opposite points of the equatorial edge from which the condensations appear to issue and stream off in a spiral curve. The physical reasons for the equiangular spiral form of the nebular arms are uncertain but the observational evidence admits of no doubt that they are almost universally present.

The proper motions of the condensations in the spiral arms of several nebulae measured by Van Maanen, make it very probable that this motion is outward along the arms, proportional to the distance from the central nucleus, and corresponds to a rotation period on the average of nearly 100,000 years. Jeans has very recently discussed these observed motions mathematically, and has shown that they may be produced by a central force inversely proportional to the square root of the distance, markedly different from the force of gravitation. This curious result may of course be due to uncertainties in the very small motions observed and too much stress should not be placed on the reality of this peculiar law of force.

Jeans has, however, established, based on the probable physical conditions of the matter in the spiral arms, how far apart the condensations should be and this evidently gives us a clue to the distance of the spirals, confirmed by independent methods. An analogous analysis shows that the average mass of one of these condensations will be of the order of 10^{34} grams, a mass comparable with the average star, the sun being 2×10^{33} grams. He further shows that the density of the central nebular nucleus is about 4 times 10^{-17}grams per cubic centimetre. By terrestrial standards this density is incredibly low but nevertheless will correspond to about a million molecules per cubic centimetre and a mean free path of 2000 km. It easily follows from these results that the mass of the spirals is of the order of 100,000 times and may be in some cases millions of times the sun.

We may hence consider, with reasonable probability, that each of the thousands of spiral nebulae in the sky is thus projecting into space condensations or nuclei of extremely tenuous matter of the same order of mass as the stars and which we must believe eventually develop into the stars. It appears that these nuclei, owing to their very low density soon become non-luminous but that the inevitable subsequent though slow gravitational condensation and the aggregation of adjacent nebular matter will cause an increase in the mass, density, temperature and rotational velocity. Jeans has traced, by further mathematical treatment, the subsequent development of those nuclei with sufficient mass and angular velocity, and has shown that they may develop into rotating ellipsods, pear shaped figures and final division by fission, forming double stars. Although the analysis is not complete, astronomical observation shows its high probability as at least one star in four or five is a close double and in the very massive B and O-types the proportion approaches one-half. Further evidence is afforded by certain eclipsing variables which are shown by analysis of their light curves to be almost in contact and hence probably recently divided.

Physical Conditions in the Stars

Having thus sketched the probable origin of the aggregations of matter from which the stars originate, it is now in order to attempt to trace their subsequent development and the steps in their evolution. The mathematical and physical treatment of the conditions at the surface and in the interior of the stars we owe to another famous English astronomer, Eddington. Every member of this section is doubtless aware of the usual explanation of why the stars are hot and is familiar with the old idea of the maintenance of solar and stellar heat by contraction. Eddington has, however, placed these ideas on a much sounder basis and has removed many of the difficulties by taking account of the previously unrecognized factor of radiation pressure, aetherial pressure as he calls it, and has developed a beautiful and complete theory of the conditions in the interior of the stars.

It is impossible to go into the details of this theory and it must suffice to state that it takes account of the gravitational pressure inward opposed partly by molecular motions, the elasticity of the gas, and partly by radiation pressure. The radiation outward is obstructed by the opacity and the dissociation of the atoms at the enormous temperatures in the interior has also to be allowed for. Taking account of these factors, he has calculated the conditions of density and temperature in the interior of an average giant star, which are given in the accompanying table, while in very massive stars the central temperatures may reach as high as 20,000,000 degrees. At these high temperatures, radiation pressure becomes a large proportion of the total pressure and the opacity also becomes high on account of the exceedingly short wave length of the radiant energy corresponding to soft X-rays. Eddington has calculated that a layer of gas of the density of the terrestrial atmosphere and only 6 inches thick would absorb 95 per cent of this radiation.

Mass=1.5 Sun: Density=0.002: Type F7: Temp.=7500°K

Distances from centre	Density	Temperature
0	0.1085	4,650,000°K
.145	.0678	3,980,000
.290	.0215	2,710,000
.435	.00503	1,670,000
.58	.00100	974,000
.725	.000149	517,000
.87	.0000093	207,000
1.00	.000000	

The importance of mathematical physics in obtaining a picture of the conditions in the interior of a star, forever inaccessible to direct observation, has been clearly shown by Eddington. He assumes a physicist on a cloud-bound planet, who can know nothing of the stars, setting to work to calculate from laboratory data only the relative proportions of aetherial and molecular pressure in globes of gas of various masses. This calculation, given in the accompanying table, does not depend in any way on astronomical data and shows that radiation pressure is insignificant for masses below 10^{33} grams and overpowering beyond 10^{35} grams.

Gaseous Globes of Various Masses; Sun=2x10^{33} grams.

Mass of Globe	Radiation Pressure	Molecular Pressure
10^{30} grams	0.00000016	0.99999984
10^{31}	.000016	.999984
10^{32}	.0016	.9984
10^{33}	.106	.894
10^{34}	.570	.430
10^{35}	.850	.150
10^{36}	.951	.049
10^{37}	.984	.016
10^{38}	.9951	.0049
10^{39}	.9984	.0016
10^{40}	.99951	.00049

If the veil of cloud is now removed the physicist on looking up into the skies sees a thousand million globes of gas, the stars, practically all of mass between 10^{33} and 10^{35} grams. The lightest known star is just below 10^{33} and the heaviest, an O-type, 6°1309, discovered by me is 1.5 times, 10^{35} grams. For globes much below 10^{33} grams the temperature will not rise high enough for visibility, while beyond 10^{35} grams the radiation pressure becomes so nearly equal to the gravitational pull as to produce instability. It is of interest to note that the average mass obtained by this calculation for the stars is identical with the mass of the nebular condensations calculated by Jeans.

It has been further shown by Eddington that as long as the star remains relatively diffuse so that the gaseous material obeys the ordinary gas laws, the total brightness remains nearly constant and is a function of the mass only between the limits of visibility at a temperature about 3000°, when the star is an enormously distended globe of mean density of the order of a millionth of water on the one hand, to a temperature of some 20000° and a density about a tenth of water on the other. This and the previous theoretical results are practically confirmed by astronomical observation. It should be mentioned, however, that the astronomical data generally antedated the theoretical, and it seems possible that the trend of the theoretical development may have been partially guided by astronomical results.

Astronomical Theories of Stellar Evolution

It is now time to consider more particularly the part played by astronomy in the development of the theory of stellar evolution.

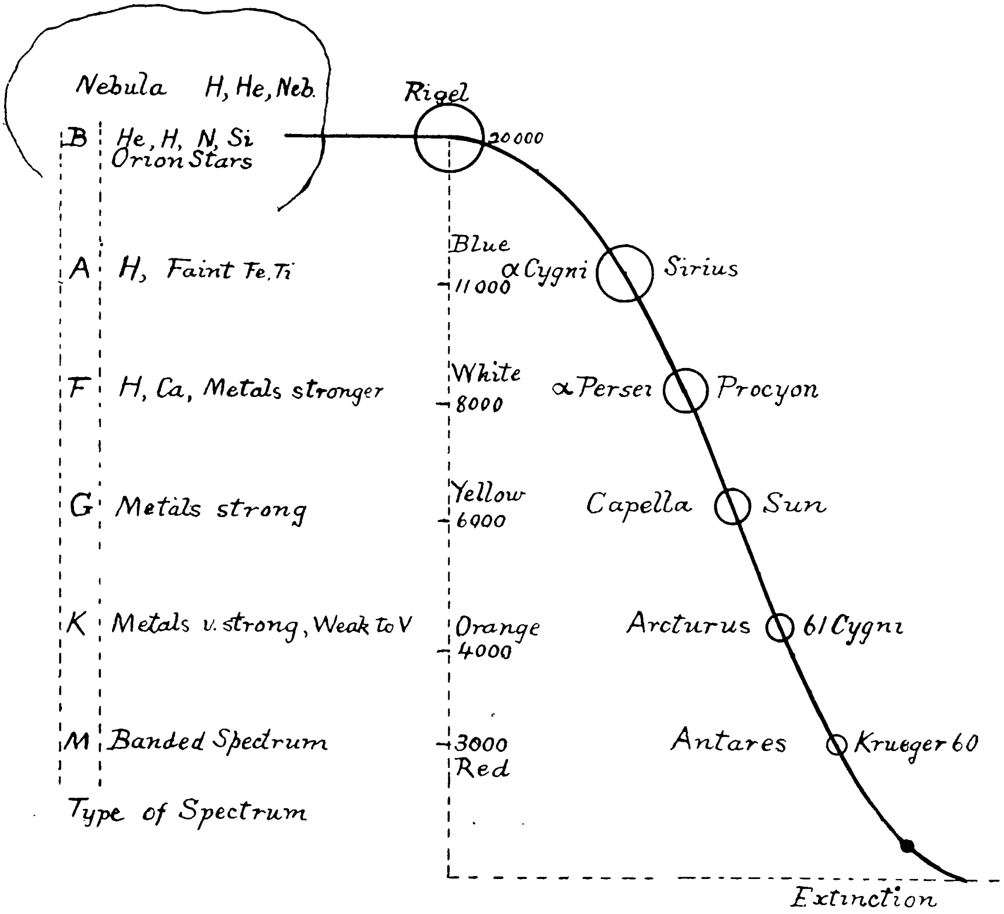

Figure 7

Astronomers by painstakingly accurate and long continued observations have accumulated data concerning the apparent and absolute brightness, the tangential and radial motions, the distance and dimensions, the temperature and other physical conditions, and the sequence of spectra in a limited number of stars. By masterly generalization they have combined this scattered information into a comprehensive theory of stellar evolution. After the application of spectroscopy to the stars, the first theory to be developed which held nearly undisputed sway until about ten years ago, postulated the condensation of the stars from the gaseous and not the spiral nebula. The initial stage then was an intensely hot and tenuous blue star at the maximum stellar temperature, increasing density, decreasing volume and diminishing luminosity through the white, yellow and red stars to extinction, as diagrammatically represented in a general way in Fig. 7. The English astronomer Lockyer and his associates were practically the only dissentients from this view, strongly insisting upon both an ascending and descending temperature scale. His ideas were evidently in advance of the times and there were in addition some difficulties in his theory to account for its non-acceptance. It remained for Hertzsprung and Russell, chiefly the latter, who has been the principal agent in converting astronomers to the new view, to formulate and substantiate the "giant" and "dwarf", the ascending and descending scale theory of stellar evolution.

According to Russell, these globes of gas of various masses between 10^{33} and 10^{35} grams, probably formed from the spiral nebulae in the manner described by Jeans and developing according to the physical laws formulated by Eddington, would eventually come, after aeons of time, to visibility as deep red stars of low density and large volume. We have the positive evidence of the existence of such enormously distended globes, such "giant" stars, in the measured dimensions of Betelgeuse and Antares, some three hundred million miles in diameter and of a mean density about the thousandth of an atmosphere. Condensation and increase of density and temperature continue and we have the red stars changing to orange like Arcturus, to yellow like Capella, to white like Alpha Persei, and to blue like Vega, Rigel and the other bright stars in Orion. Only the more massive of the stars, about ten times the solar mass, can reach the brightness and temperature, 15000°—2000°, of the stars in Orion. Stars of mass two or three times the sun can only reach the white stage, the sun itself was probably never hotter than 7000°, while stars of mass much less than the sun cannot rise much beyond the red stage and some indeed may never come to visibility.

All the stars in the stage of ascending temperature are called "giants", the term referring not to mass but to the great volume due to the low density of these bodies. The maximum surface temperature reached in this stage of development depends, as previously indicated, upon the mass and seems to be attained when the density reaches about one-tenth that of water. At this point it had hitherto been assumed that the ordinary gas laws begin to fail and continuing condensation can only result in decreasing temperature and luminosity. The stars now called "dwarfs" will pass in the reverse order

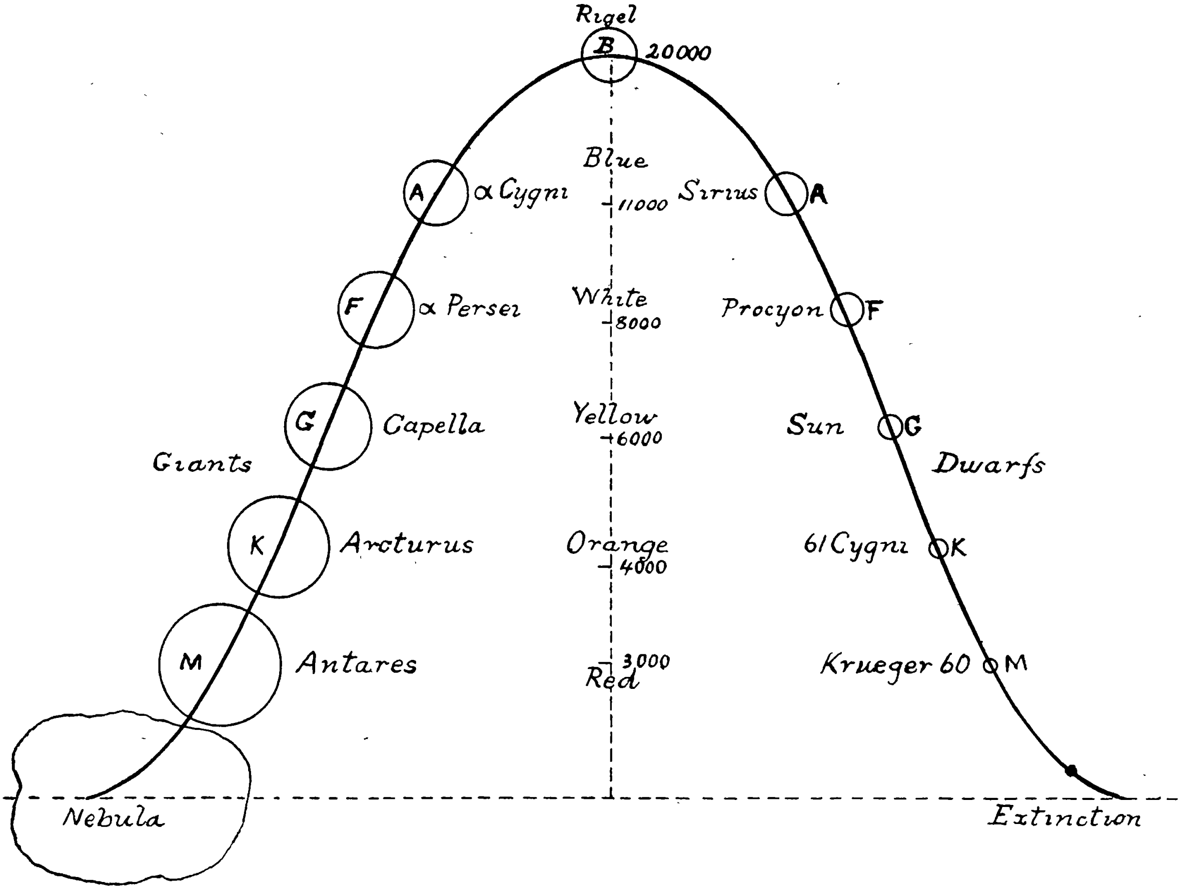

Figure 8

from blue through white, yellow, orange and red to extinction, our sun being a dwarf yellow star. A graphical representation of the stages through which a fairly massive star may pass in its development according to the giant and dwarf hypothesis is given in Fig. 8.

A paper read by Eddington at the March meeting of the Royal Astronomical Society makes it appear now, however, as if the dwarf stage of this theory may require modification. He apparently establishes theoretically and confirms it by observational data from double stars, Cepheids, and eclipsing variables, that even in the dwarf stage with a density several times that of water the stars still obey the gas laws. This unexpected behaviour is reasonably explained by the loss of the outer rings of electrons from the atoms of the elements owing to the tremendous temperatures in the interiors of the stars. The volume of the atom is hence reduced approximately a hundred thousand fold and the enormously closer packing possible obviously permits the gas laws to be obeyed even in the densest dwarfs. How much change this revolutionary paper will entail in the dwarf stage of the evolutionary scheme is not yet apparent but there seems no doubt that considerable modification will be required. I may be pardoned for mentioning that one of the principal observational supports of this new development was obtained from the dimensions of eclipsing variables determined by me at Victoria some three years ago.

The Position of O-Type Stars in the Evolutionary Sequence

The results above mentioned do not appear, however, to affect the place of the O-type stars in the evolutionary scheme. This remarkable group of stars is very limited in number, forming less than one-tenth of one per cent of those whose spectral type has been determined, and they have always been considered exceptional in their physical and spectral characteristics. They may be divided into two distinct though allied sub-classes, the emission O-type, Wolf Rayet, stars, whose spectra are uniquely characterized by broad bright bands with no absorption and the absorption O-type stars with spectra containing absorption lines and occasional narrow emission lines. The elements present are the same in both classes and consist principally of hydrogen and helium and of ionized helium, carbon, nitrogen, oxygen and silicon. A third sub-class may perhaps properly be included, the planetary nebulae whose central nuclear stars are always emission or absorption O-types.

The presence of lines or bands in the spectra of this group due to the ionized atoms of the principal non-metallic elements is practically peculiar to this group, indicates clearly the exceptional position in the spectral sequence and the extreme temperature, considerably higher than any other spectral class. While the O-type stars have for many years been generally considered as probably a continuation of the spectral and evolutionary sequence beyond the B-type, Orion stars, there has been some evidence pointing to a smaller absolute magnitude, total brightness, for the O than the B-type, directly contradicting this idea. However, a careful analysis by H. H. Plaskett two years ago unmistakeably showed their continuous progression in spectral characteristics and temperature beyond the B's while the present investigation clearly proves their progression in mass and luminosity and places them at the head of the evolutionary sequence as undoubtedly the hottest, brightest and most massive of the stars.

It will be of advantage to briefly summarize in turn some of the results obtained from this investigation with respect to the masses, motions, distances, distribution and luminosity of the O-type stars, with the application of these data in the evolutionary theory, and to discuss finally the relations of the three sub-classes above described.

Mass—It has been shown previously from double star data that the average mass apparently increases with temperature. Yellow G-type stars like the sun, temperature 5000° – 6000°, average about the solar mass; white F-type stars like Alpha Persei and Procyon, temperature 8000° – 10000°, have two or three times the sun's mass; blue-white A-type s ars like Vega and Sirius, temperature 10000°—12000°, have four or five times the solar mass; and the blue B-type stars, such as Bellatrix and Rigel with temperatures around 15000° average about ten times the mass of the sun. The present investigation has shown that this progression in mass has continued in the much hotter O's with temperatures variously estimated from 20000° to 30000°. From orbital data of several O-type spectroscopic binaries it seems certain that they are much more massive than the B's, ranging probably between 10 and 80 times the solar mass, with an average value about 40. The most striking example is the double system 6°1309 with minimum masses of 75 and 63 times the sun for the two components. These great masses for the O-type stars with the necessarily higher temperatures, which are both theoretically predicted and spectrally substantiated, undoubtedly place this remarkable group at the apex of the evolutionary sequence, to which only such very massive stars can attain. The fact that there are twenty times as many A-type as B-type stars and probably twenty times as many B-type as O-type stars tends to confirm this conclusion as rapid decrease of numbers with increase of mass is probable. No stars of greater mass or higher temperature than the O's are known and it seems necessary to assume that the evolution beyond them must subsequently follow a course of decreasing temperature and luminosity.

Motions—The O-type stars are exceptional in their motions as compared with the progression in velocities of the other spectral types. The residual radial velocities of the more common types are in kilometres per sec. M=17, K=17, G=15, F=14, A=11, B=6.5. If the same progression were followed, we should expect the O's to be only 4 or 5 km. but the present investigation gives a residual radial velocity of 25.5 km. for the absorption O-types. The emission O's are immeasurable while the planetaries have a velocity of 30 km. These stellar velocities are only exceeded by the red variables which have velocities of about 35 km. The discontinuity between the velocities of the O and B-types is unexplainable, unless it be assumed as depending in some manner on the distance for, as we shall see in the next paragraph, the O-type stars are four or five times the distance of the B's. The tangential or proper motions of the O's are exceedingly minute, only approached by another limited class, the N's, at the other end of the spectral sequence.

Distance and Distribution—The O-type stars are so remote from the sun that the ordinary trigonometrical method of determining distance is useless and recourse must be had to statistical methods of obtaining the average distance or mean parallax of the group.

By three different methods of combining the radial velocities and proper motions of the O-type stars the mean parallax was computed as 0″.0011 corresponding to an average distance of 3000 light years, nearly five times as far away as the B's, seven or eight times the average distance of the other common types and only equalled in remoteness by the N's, deep red giant stars at the other extreme of stellar temperature and equally limited in numbers. In distribution the O-type stars are very closely confined to the plane of the galaxy, but fairly uniformly spaced in galactic longitude. They appear hence to form an annular disc in the plane of the milky way of an average radius of 3000 light years, entirely beyond the other naked-eye stars and, while the N-type stars are about the same average distance, they are not so closely limited to the galactic plane. It is perhaps worth while pointing out that the higher radial motions of the O's are what would be expected if the galaxy were considered as formed from an enormous spiral nebula with a law of motion varying with the distance from the centre similar to that found in the observed spirals. Another possible explanation may be supplied from Silberstein's recent discussion of space time curvature. According to this the Doppler displacement in the stars is the sum of two factors, the one due to the radial motion of the star and the other directly proportional to the distance of the star and inversely proportional to the radius of curvature of space time. For the O-type stars at 3000 light years this latter factor is about 10 km. thus reducing considerably the discrepancy between the O's and B's.

Luminosity—It will be of interest as illustrating modern astronomical methods to describe briefly the three methods employed in determining the luminosity, the total brightness or the absolute magnitude, as it is technically called, of the O-type stars. The "absolute magnitude" is defined as the apparent magnitude a star would have at a distance of 10 parsecs, 32.6 light years, remembering that the sun at that distance would be about 4.9 magnitude.

The first and probably the most reliable method of determining the absolute magnitude depends upon a simple application of the inverse square law to the apparent magnitude when the distance is known. For example if an O-type star at a distance of 1000 parsecs has an apparent magnitude of 4.9, the same as the sun at a distance of 10 parsecs, it is obviously 100^2 or 10000 times as bright as the sun and has an absolute magnitude of – 5.1. Using by a similar method the average apparent magnitude with the mean parallax or average distance obtained above, the average absolute magnitude of the O-type stars is easily determined as –4 corresponding to a brightness 4000 times the sun. This is an average value and from various considerations the individual values have a range of about 3 magnitudes or between say 1000 and 15000 times the sun's brightness.

The second method is an application of Eddington's theoretical treatment of giant stars based on considerations of the radiant energy, opacity and average molecular weight of stars of known mass and gives an absolute magnitude of – 1.9, 600 times the sun for a star of mass 10, and absolute magnitude —47, 8000 times the sun for star of mass 80. The average value is – 3.7, 3000 times the brightness of the sun by this method, in fairly close agreement with the first.

The third method, partly theoretical, depends on data or estimates of mass, density and surface brightness for these stars, and the total brightness can obviously be simply calculated when these three factors are known. The mass has already been accepted as varying between 10 and 80 times the sun. The density, from data obtained from eclipsing variables, modified by consideration of the high radiation pressure in these tremendously hot and massive bodies, probably lies between the values of one-tenth and one-hundredth of the sun, likely nearer the lower value. The surface brightness can be calculated from radiation laws when the temperature is known, assumed in this case as 20000°, and has also been determined for stars of various types by several different methods by Russell. The two determinations agree fairly well in making the surface brightness of an O-type star -3.75 magnitudes, over 30 times brighter than the sun per unit area. For density one-tenth, the average brightness of stars 10 to 80 times the solar mass is about 2000 times the sun and for density one-hundredth nearly 10000 times the sun's brightness.

Combining all three methods, with the greatest weight to the first, gives the average luminosity of the O-type stars as 4000 times the sun, several times brighter than any other spectral class and again confirming their exceptional position in the theory of stellar evolution.

Relations of the Sub-Classes—The spectra of the O-type stars has already been briefly described, its super-enhanced nature pointed out and the differences between the absorption and emission sub-classes referred to. All the information just discussed about mass, velocity, distance and luminosity refers only to the absorption O's as in the emission O's or Wolf Rayet stars no such data can be obtained owing to the breadth and mixing of the emission bands. The physical cause producing such wide bands in the Wolf Rayet stars is obscure as with the low order of pressure now accepted for stellar atmospheres, it is obviously impossible of explanation as a pressure effect. Previous attempts at the spectral investigation of these mysterious objects, the most puzzling in the sky, with the possible exception of the Novae, have not resulted in much advance and it seemed worth while, as a considerable number of spectra were obtained in the course of this investigation, to examine the relationships between them and the absorption O's.

Some advances appear to have been made by this analysis. The majority of the broad bands have been identified and shown to be analogous in constitution and state of ionization to the absorption O's. The Wolf Rayet stars observed have been arranged in order of excitation and shown to be generally similar in this respect also to the absorption O's. From the analysis of some transition examples between the two sub-classes it appears probable that the Wolf Rayet stars develop as a sort of side chain from the absorption stars, and apparently at any stage of the temperature sequence of the latter. The physical causes producing this change from absorption to wide emission are obscure but the apparently accidental development does not seem to be a function of the temperature. It is possible that mass may have something to do with it but unfortunately we know nothing of the mass of the Wolf Rayet stars, although the third sub-class, the planetary nebulae with O-type nuclei, appear to be even more massive than the absorption O's.

So long as one can keep an open mind on such a question, it is fascinating and perhaps useful to speculate on the effect of exceptional mass on the subsequent development of an absorption

O-type star. Radiation pressure approaches equality with the gravitational force for masses over 50 times the sun and it may be that the resulting instability is one of the causes of the eruption of emissive material eventually producing a Wolf Rayet star. From the transition examples observed, this emission appears to gradually blot out both the absorption and continuous spectrum until practically only the wide emission bands remain, which may account for the probably lower luminosity of the Wolf Rayet stars. When it is considered that the planetary nebulae are probably considerably more massive than the absorption O's, that their radial velocities are nearly the same and that their nuclei are always O-type stars, it does not seem unreasonable to assume that the surrounding nebulosity may have been produced by excessive radiation pressure "blowing out" the outer layers of the star. As a matter of fact Campbell's "hydrogen envelope" star 30°3639 appears almost like one caught midway in the process, an excellent transition example. It must not be forgotten, however, that these are speculations with little supporting evidence and many opposing phenomena. However, the possibility of such speculative support of the analogies in the three sub-classes, only adds to the evidence of their unique place in the evolutionary sequence.

Stationary Calcium and Sodium—Although apparently without direct bearing on the question of stellar evolution, another result of this investigation should be briefly referred to. In practically all absorption O-type and Wolf Rayet stars observed and in many of the "early" B's there appear in the spectrum sharp and narrow H and K lines of calcium and also wherever tested sharp and narrow D_1 and D_2 of sodium. The sharpness and the stationary position of these lines as contrasted with the diffuseness and the shifting position of the star lines unmistakably points to a practically stationary origin outside the stellar atmospheres. The only possible explanation seems to lie in the presence of very widely, almost universally, distributed but exceedingly tenuous clouds of matter throughout interstellar space; practically at rest with respect to the stellar system. All the stars are moving through these clouds with varying speeds but only the very high temperature stars such as the O's or early B's have sufficient exciting power to produce the sharp calcium and sodium absorption lines. It may be added that such a stationary cloud has been suggested, perhaps not very seriously, as possibly forming a fixed reference system in space.

In conclusion it may, I think, be safely stated that sufficient evidence has been obtained from this investigation of the O-type stars to definitely place them at the apex of the evolutionary sequence, and to show the great interest and importance of this very limited class.