The Temperatures of the Stars.

By Herbert Dingle.

The measurement of the temperature of a star is one of the most difficult problems of physical astronomy. The difficulties are of two general kinds. In the first place, the very phrase, "the temperature of a star," has no meaning: we may as well speak of the latitude of the land surface of the earth. There can be no doubt whatever that the temperature varies from one part of a star to another over an enormous range—probably thousands of times greater than the interval between the temperatures of liquid hydrogen and the electric furnace. Secondly, for experimental methods of measurement the only available data are wrapped up in an inconceivably small fraction of the total radiation of the star which reaches the earth after the possible wear and tear of many years' journey through interstellar space and our own atmosphere. From the character of that radiation we have to deduce the temperature of the star. From these two general sources difficulties of many kinds issue forth.

Happily, the resources of modern physics make the problem anything but hopeless. The "temperatures" of a number of stars have been determined by different methods, though exactly what the figures mean, and how much reliance can be placed on them, are perhaps still matters of doubt. With regard to the first source of difficulty, considerable help is received from the spectroscope. More than ninety-nine per cent. of recorded stellar spectra consist of absorption lines on a continuous background—conclusive evidence that a star consists of at least two distinct parts. In the light of Kirchhoff's principle, the continuous spectrum is attributed to the hotter, deeper-lying part, and the absorption lines to a surrounding cooler, but still luminous, atmosphere. Accordingly, temperatures measured from the characteristics of the absorption lines must apply to the atmosphere, and temperatures measured from the continuous spectrum must apply to the interior.

The next questions are evidently: Do the atmosphere and the interior, as thus defined, comprise the whole star, or are there regions outside the one and beneath the other? In the former event, what parts of the atmosphere and the interior have the respective measured temperatures, and, in the latter event, what are the temperatures of the unconsidered regions? For the answers to these questions we are indebted mainly to the nearest star—our sun. We know, from observations made possible by a total solar eclipse, that outside the sun's atmosphere (*i.e.* the source of the absorption spectrum lines) there is the corona—evidently a permanent though ever-changing part of the solar structure. We know also that the source of the sun's continuous spectrum is effectively a layer of limited thickness near the surface, because the luminosity of the sun's disc does not fall off appreciably outwards from the centre until the limb is nearly reached. There must, therefore, be a core inside what we have called the "interior," about which, from direct observation, we know nothing. We may assume, then, that in addition to the regions the temperatures of which we measure from the spectrum of a star, there are other very extensive regions, the temperatures of which it is at present quite impossible to determine by any experimental means.

The temperature throughout the atmosphere of a star may be regarded as a constant quantity. To solar eclipses, again, we owe the knowledge that the sun's atmosphere is very thin compared with the depth of the whole globe. It is true that there are indications that its physical condition varies at different levels, but these variations are refinements of analysis which we cannot hope to apply to the stars for a long time to come. If we can determine a temperature from the absorption lines in the spectrum of a star, we are justified in supposing that we can state definitely the temperature at a particular part of the star. The case is not so clear when we come to the continuous spectrum. We do not know at all definitely from what part of the star the continuous spectrum comes. We know that it must come from beneath the atmosphere, and it has just been pointed out that it represents the radiation of a surface layer, which we may call the "photosphere," but how thick that layer is, and what part of it has the temperature deduced from its spectrum, are questions that are still unanswered.

The first set of difficulties, then, can be partly overcome. Assuming that the sun is a type of its kind, we can divide a star into four distinct parts—a corona, an atmosphere, a photosphere, and a core. Of the temperatures of the first and last, we know, by direct experiment, nothing. The temperature of the second can possibly be measured definitely, and that of the third, vaguely. Supposing these measurements to be made, theory indicates, for certain stars, what must be the temperatures at different parts of the core.

Turning now to the second set of difficulties—those connected with the actual measurement of the temperatures—we note that these may be subdivided into the difficulties of obtaining the requisite data, and those of interpreting the data when they are obtained. It is probably fair to say that, in measuring atmospheric temperatures, the former preponderate, while the latter are most in evidence in the measurement of photospheric temperatures. It was Lockyer who first showed the influence of temperature on the line spectrum of a substance, and urged that the relative temperatures of stellar atmospheres could be determined from a study of the lines by which particular substances were represented. More recent investigations, originated by Saha, have confirmed Lockyer's views, and have shown how the actual temperatures can be calculated. But it appears that, while temperature is probably the chief factor in determining the line spectrum, it is by no means the only one. Pressure, the absorption of photospheric radiation, the relative amounts of different substances in the atmosphere, the ionisation potentials of the elements—these at least play a part, and must be determined before the temperatures can be found. Unfortunately, they are, in most instances, unknown, and their values have to be assumed, on more or less plausible grounds. There is, therefore, a considerable element of uncertainty in existing estimates of the temperatures of stellar atmospheres.

The temperatures of the photospheres are deduced from the distribution of energy in the continuous spectra. Laboratory experiments on black-body radiation show that the spectrum of a perfect radiator at uniform temperature is characteristic of the temperature. Wien's displacement law states that the wave-length of the radiation carrying the maximum amount of energy is inversely proportional to the absolute temperature of the source of radiation, and Planck's radiation formula expresses, with great accuracy, the distribution of energy throughout the spectrum. Assuming that the photosphere of a star bears the same relation to its continuous spectrum as does the equivalent of a black body in the laboratory, the photospheric temperatures are found. Wilsing and Scheiner, of Potsdam, and Nordmann, of Paris, have used the method, and Sampson has recently shown that, by employing a photo-electric cell as an energy detector, the accuracy of the measurements may be greatly increased.

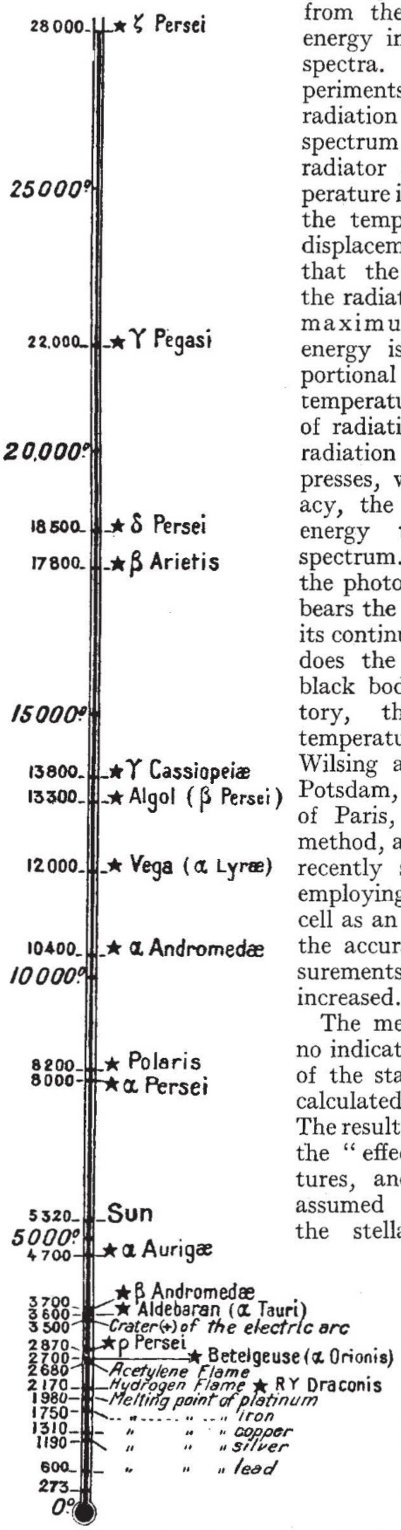

FIG. 1.—Scale showing, in absolute centigrade degrees, the temperatures attained in certain terrestrial processes compared with the effective temperatures of representative stars.

The measurements give no indication of the region of the star which has the calculated temperature. The results are spoken of as the "effective" temperatures, and are generally assumed to characterise the stellar surfaces, immediately beneath the atmospheres. Two remarks might be made concerning them. First,—granting for a moment the validity of the method of measurement, they represent minimum temperatures only, for if the stars are not perfect radiators, their temperatures must be higher than the calculated ones. Second,—it is a somewhat dangerous assumption that the resultant radiation from a globe of gas, perhaps millions of miles in depth and varying in almost every physical quality from point to point, will give a spectrum comparable with that of a thin solid surface at a uniform and probably very much lower temperature. We know practically nothing as yet of the processes of production of continuous spectra. We have no means of distinguishing one such spectrum from another except by measuring the distribution of energy in it; yet it is certain that there may be profound differences in the modes of origin. The continuous spectra of a cold fluorescent body, of an electric glow-lamp, of hydrogen radiating also the Balmer series—here at least are three spectra which probably have nothing in common except their appearance. The stellar nuclei of planetary nebulae, again, give spectra which suggest the operation of the classical laws of radiation rather than those of the quantum theory, unless the stars have temperatures so high that no one is prepared to accept them.

It is noteworthy, however, that the atmospheric and photospheric temperatures, estimated by totally different, and at best approximate, methods, are of the same order of magnitude. Fig. 1[1] shows, on a thermometric scale, the range of temperatures covered by present measurements. Temperatures have been measured at almost all points intermediate between the absolute zero and the temperature of ζ Persei. The cores of the stars, according to Eddington's theoretical researches, reach temperatures far too high to appear on the scale. It is probable that there are bodies in the universe at all temperatures between absolute zero and 20 million degrees centigrade or higher.

Whatever may be said of the absolute accuracy of stellar temperature measurements, it is scarcely questionable that they show the true order in which the temperatures are arranged. There is no doubt whatever that Vega is hotter than Aldebaran in corresponding regions. Consequently, if the order of stellar evolution can be established from other data, it becomes possible to determine the changes of temperature of a star throughout its life. Russell's well-known theory of evolution takes the order of increasing density of a star to be its order of development: contraction is a continuous process from childhood to old age. This implies that a star passes twice through the same series of spectral types, and therefore through the same series of temperatures. Beginning as a huge, rarefied, cool mass of gas, it contracts and becomes hotter until a stage is reached when it is too dense to obey the laws of a perfect gas. The temperature then soon reaches a maximum and begins to fall—contraction, however, continuing, though at a slower pace—and the star retraces its path through the sequence of spectral types which it traversed on its upward journey. While the temperature is rising, the star is a "giant," and after it begins to fall the star becomes a "dwarf." The career of a typical star, with time as abscissa and temperature as ordinate, is pictured in Fig. 2: continuous contraction is indicated by the decreasing diameter of the circles representing the star.

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[1] The diagrams illustrating this article are adapted, by kind permission of Dr. Charles Nordmann, from an article by him on "La vie et la mort des étoiles," which appeared in *L'Illustration* of April 7, 1923.

The temperature reached at the maximum point depends on the mass of the star: the greater the mass, the higher the temperature and the longer the stellar life. Fig. 3 illustrates the careers of the sun and of stars the masses of which have nearly the extreme values found in Nature. Probably a star having a mass less than one-tenth of that of the sun would not become hot enough to be seen, while Eddington has shown that stars much more than ten times as massive as the sun would be unstable. Only the most massive stars can reach the B and Oe 5 stages of the Harvard spectral sequence. The lighter stars, like the sun, turn back at the A condition, or even at a still lower stage.

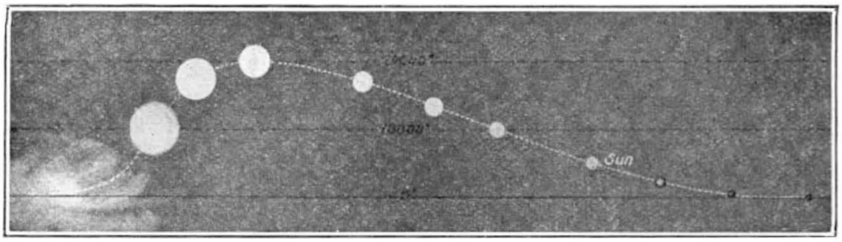

FIG. 2.—Diagrammatic representation of the theoretical development of a massive star from an original nebula to a final cold, dense body. The dotted curve is to be regarded as identical with the highest curve in Fig. 3.

Temperature appeared at first, in this great stellar drama, to play a dependent rôle. The star developed heat by contraction, and radiated heat into space. So long as the amount of heat developed exceeded the amount radiated, the temperature would rise, and when, through retardation of contraction and increase of radiation, the conditions were reversed, the temperature would fall. This view is satisfactory in every respect but one—it indicates a length of stellar life far shorter than geological and other evidence makes it possible to admit. In order to account for the amount of heat which a star radiates during its immeasurably long life, it is necessary to suppose that the heat generated by contraction is supplemented by an enormous supply of energy from some other source. Nothing is certainly known of the nature of this supply. Possibly, as Eddington proposes, it is to be found in the formation of heavier elements from hydrogen. But, wherever the energy comes from, it is difficult to avoid the hypothesis that it can be released only at the extremely high temperatures attained near the centres of stars. Contraction raises the temperature of a star up to a certain point, and then temperature takes charge and sets free energy from the unknown source at a rate almost equal to the rate of radiation, so that the star is in a condition of approximate equilibrium. It is a problem for the future to determine the origin of the almost inexhaustible supply.

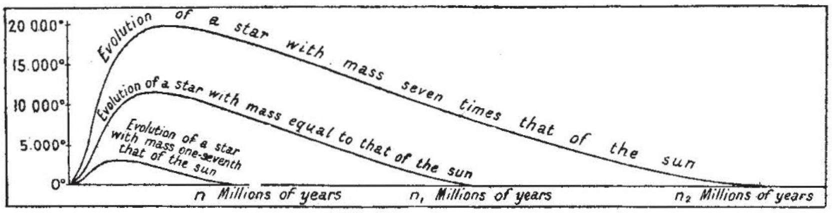

FIG. 3.—Curves illustrating the course of evolution of stars of differing mass, showing that, the more massive the star, the longer is its life and the greater is the range of temperature through which it passes.

Man and Scottish Animal Life.[1]

By Dr. JAMES RITCHIE.

IN the opportunity it affords for the study of the part man plays in the evolution of a fauna, the animal life of Scotland stands alone. This is largely due to a series of geological accidents: the Glacial Period, which made a clean sweep of former faunas; the post-glacial continental land bridge, which allowed immigration from the mainland of Europe, and the subsequent breaking of the continental connexion. Thus there was isolated on the *tabula rasa* of Scotland a fair sample of the post-glacial European fauna, which henceforth was removed from the possibility of subsequent migrations such as complicate the history of continental faunas, and the later evolution of which must in general be due either to the influence of physical and organic changes limited in time and space, or to the interference of man.

The influence of man was itself strictly limited in time, for the earliest human settlements so far recognised in Scotland date back only to Azilian times. It was also unequal in its incidence, gaining in intensity with the passing of time. Thus during the Neolithic, Bronze, and early Iron Ages only some four of the larger members of the original fauna disappeared—the giant fallow deer, the lynx, the lemming, and the rat vole—and it is doubtful whether the disappearance of any of these was due to man's presence. We may say, therefore, that when the Roman legions followed Agricola northwards through the marshes of Scotland in the early years of our era, they found a fauna which, except for the presence of primitive domesticated animals, differed little in kind from that which greeted man on his first arrival in Scotland some 8000 years before. But the following centuries saw more rapid changes, which so increased that by the sixteenth century many new and important elements had been added, while most of the larger members of the old fauna had been swept away, with the extermination of such as the reindeer, the elk and the wild boar, the brown bear and the beaver, the great bustard, the crane and the bittern. Nowadays the content and assortment of the fauna, the relative numbers of its members and their distribution, show little resemblance to the conditions of the original post-glacial immigrants.

The degree of man's interference may be compared

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[1] Summary of an address delivered at the request of the Council to the Royal Society of Edinburgh on July 2.