The Evolution of the Stars.

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ABOUT a year ago (*NATURE*, December 6, 1924) reasons were given for supposing that the source of stellar radiation is to be found in the annihilation of stellar matter. Subsequent investigation suggests that the same hypothesis can clear up the puzzle of stellar evolution and of the spectral changes of a star.

In the early days of stellar spectroscopy, the spectrum of a star was believed to be an index to the star's age. That the spectra of different types of stars showed lines of, say, hydrogen, calcium, and titanium oxide, was explained by the supposition that as a star aged, its composition changed, by transmutation of the chemical elements, from hydrogen into calcium, from calcium into titanium oxide, and so on. We know better now; the researches of Saha and others have shown that a star's spectrum is an index only to the temperature of its surface. The solar spectrum shows calcium lines merely because the sun's outer layers happen to be at a temperature at which calcium atoms are very active in absorbing and re-emitting radiation; if the temperature of these layers were suddenly doubled, their spectrum would consist mainly of hydrogen lines, while if the temperature were halved, the spectrum would be dominated by the titanium oxide bands. The various types of spectra might quite well be expressed merely as temperatures, except for some outstanding difficulties as to the correct calibration of the temperature scale. Thus the problem of explaining the spectral changes of a star reduces to that of tracing out the sequence of temperatures assumed by its surface.

When we attempt to interpret radiation in terms of the annihilation of matter, the first observational fact that confronts us is that the radiations of the stars are nothing like proportional to their masses; for example, the very hot star V Puppis radiates nearly 1000 ergs a second for each gram of its mass, the sun about 2 ergs, and the earth certainly less than $\frac{1}{100000}$ erg. The transformation of matter into radiation clearly proceeds at very different rates in different bodies.

Our first impulse is perhaps to conjecture that the rate of transformation may be expedited by high temperature. But considerations of stability are found to prohibit any substantial effect of this kind. We can see in a general way that if a rise of temperature resulted in more rapid transformation, then any slight local excess of generation of energy, by raising the temperature, would force a still greater excess generation of energy, and so on without limit. Precise mathematical investigation (*Monthly Notices, R.A.S.*, October 1925, p. 914) shows that the observed stability of the stars permits of at most a very slight increase of this rate of transformation with temperature, and even this seems to be ruled out by physical considerations. Since matter is atomic, its annihilation must also be atomic, the annihilation of the smallest unit, a proton and electron, producing 0.0015 ergs of energy. This will form one quantum of radiation of wave-length 1.3×10^{-13} cm., which corresponds to a temperature of 7,500,000 million degrees. The temperature of a star's interior, some

ten or twenty million degrees, is perfectly insignificant by comparison, and must be deemed quite incapable of affecting the process of transformation either way, at any rate by direct methods. We must accordingly suppose that matter is transformed into radiation by a spontaneous process, which proceeds, like radioactive transformations, without any regard to temperature or density. Newly generated radiation will have a wave-length of 1.3×10^{-13} cm. or less, but will soon become "softened" by interaction with matter and will degenerate into ordinary temperature-radiation before it has travelled far through a star. Part of the radiation generated in astronomical bodies of very low density may, however, escape into space as "hard" radiation of wave-length of the order of 10^{-13} cm.; this may be the origin of the highly penetrating radiation recently investigated by Millikan.

The great range of values of radiation per unit mass cannot, then, be traced to the variations in the physical conditions of different stars; to account for it we have to suppose that stars consist of a mixture of different types of matter which radiate at different rates, and that the proportions of the mixture vary from one star to another. Those types of matter which radiate most energetically are, of course, also those which annihilate themselves most rapidly, and so are the first to disappear as the star gets old. A young star, containing a greater proportion of these types than an old star, ought to emit more radiation per unit mass. This is in actual fact observed to be the case. Our sun, then, radiates less energy per unit mass than V Puppis simply because it is seven million million years older, and in this interval the elements which are responsible for most of the radiation from V Puppis have disappeared from the sun.

Since the process of transformation is a spontaneous one, it follows that if we know the composition of a star at birth and the rate of transformation of each of its constituent types of matter, we can trace out the changes in its composition throughout its whole life; the problem is similar to that of tracing the changes of radioactivity in rocks. Knowing the star's constitution at each instant of its life, we can, of course, deduce its rate of emission of radiation.

A mathematical study of the conditions of stellar equilibrium (*Monthly Notices, R.A.S.*, January, March, and June 1925) shows that the mass M , rate of emission E , and surface-temperature T of a spherical star in equilibrium are connected approximately by an equation of the form

$$\frac{1}{2} \log E = \phi(M) + c \log T + \text{a constant}, \quad (1)$$

where $\phi(M)$ is a function of the mass, which is roughly proportional to $\log M$.

If this equation were accurately instead of only approximately true, the problem of tracing a star's evolution would be very simple. Corresponding to any assumed composition of the star at birth we can, as we have just seen, trace out the sequence of changes in the mass M and the emission E . At each instant the star will adjust itself so as to be in equilibrium by

selecting a surface-temperature T such as to satisfy equation (1). The value of T given by this equation must accordingly determine the star's spectrum at every instant and the problem is solved.

It may seem almost incredible that the theoretical solution of the problem of stellar evolution should be so amazingly simple, yet such appears in actual fact to be the case, except for certain secondary complications, five of which we now discuss. These secondary complications impart incident and richness to the problem; it is because they intervene just where observation shows them to be needed, and because

about unity, while for still cooler stars c may be negative.

Now the investigation of the star's dynamical stability shows that a configuration is stable (within limits to be mentioned later) if c is positive, but is definitely unstable if c is negative. A star becomes unstable as soon as it has cooled so far that c becomes negative.

The solution of equation (1) may be exhibited graphically as in Fig. 1. In this diagram $\log T$ and $-2\frac{1}{2} \log E$ (the star's absolute magnitude) are taken as horizontal and vertical co-ordinates. Equation (1) gives a value of M corresponding to each point in the diagram, so that each point represents a configuration of equilibrium for a star. The hottest stars are to the left of this diagram, the coolest to the right; the most luminous (which are also the most massive) are at the top, both mass and luminosity decreasing as we pass downwards. If c were strictly constant and positive, the curves along which M has constant values would be a series of parallel straight lines slanting upwards to the left. When the slight variations in c are taken into account, these lines run in the way shown by the thick lines in the diagram, the unstable parts for which c is negative being omitted. The thick curve on the right passes through the points at which c changes from positive to negative and so marks the limit between stable and unstable configurations.

Every astronomer will at once grasp the significance of this curve and of the hole it makes in the range of stable configurations. In 1913 Hertzsprung showed that the M -type (or red) stars fall into two clearly divided classes—stars of high luminosity which he called giants on account of their great size (a large surface-area being necessary to discharge so much radiation), and stars of low luminosity, the dwarfs. Between these two groups of stars lay a great gulf. Later, Russell, Adams, and others showed that the gulf extends to other spectral types, probably up to about $K4$. The theoretical curve which bounds the region of instability in our diagram cannot be drawn with great accuracy, but there seems little room for doubt that it must coincide with the boundary of the gulf between the giants and dwarfs. If so, there is a very simple reason for this gulf; stars cannot exist inside it because they would be unstable.

II. Every point of the diagram shown in Fig. 1 represents an equilibrium configuration for a star; as a star's evolution proceeds its representative point moves, and its evolutionary career can be recorded by a curve. On tracing out mathematically the evolution of a typical star in the way already explained, the evolutionary curve is found to be roughly parabolic and oriented like the dotted curve PQR in the diagram. The temperature of the star first increases until it attains a maximum at Q , then turns and decreases continuously, precisely as described by the "ascending and descending temperature" series of Lockyer. In time the star runs into the region of unstable configurations, as at R in the diagram.

When this happens, the star's internal generation of energy has become inadequate to supply its loss by radiation. Ordinarily a star would remedy this by expanding or contracting, but in this particular instance the star is already in a configuration in which its loss

FIG. 1.—The stars, which are those shown by Russell in his diagram in NATURE (August 8, 1925), are as follows: 1, Antares; 2, δ Cephei; 3, Arcturus; 4, 5, Capella; 6, Plaskett's star; 7, V Puppis; 8, Y Cygni; 9, β Aurigæ; 10, Sirius; 11, Procyon; 12, 13, α Centauri; 14, Sun; 15, 16, ξ Bootis; 17, 18, Kruger 60.

they give just the requisite modifications to the main solution, that we can feel confidence in the latter.

I. Equation (1) is based on the conception of a star's interior put forward by the present writer in 1917, according to which the atoms are very largely disintegrated, as a result of high temperature, into their constituent electrons and nuclei, these now playing the rôle of "molecules" in the quasi-gas of which the star is formed. If the temperature were so high that every atom was completely disintegrated, equation (1) would be strictly accurate, c probably being equal to 2, the value given by Kramers' and Eddington's formulæ for stellar opacity. Actual stars are not so hot as this, so that c is somewhat less than 2. For average stars like our sun the value of c appears to be

by radiation is a minimum, so that any change, whether in the direction of expansion or contraction, merely increases the rate of loss which is already too large. Equilibrium is no longer possible, and the star has to make good the deficiency in its generation of radiation by drawing upon its store of gravitational potential energy. It contracts rapidly.

The fundamental equation (1) was derived on the supposition that the gas pressure inside the star conforms to Boyle's law. The gas-molecules are, however, free electrons the diameters of which are far smaller than those of true molecules, whence it results that the stellar gas can shrink to enormously higher densities than ordinary gas before Boyle's law begins to fail. Eddington has suggested that this probably gives an explanation of the amazingly high densities observed in the stars known as "white dwarfs." The surfaces of these stars are at high temperatures and their radii so small that their densities must be thousands of times that of lead. The star the career of which we are following, when once it has become unstable, must continue to shrink until Boyle's law no longer holds even for those absurdly small molecules, the free electrons. It becomes a white dwarf.

Thus our scheme of stellar evolution demands white dwarfs and provides a niche into which they fall naturally and inevitably. At the same time it suggests views of the physics and evolution of the white dwarfs which differ somewhat from those hitherto held. Eddington and Russell have considered the white dwarfs merely as extreme cases of ordinary stellar configurations. That the two or three white dwarfs so far detected are comparatively similar to one another must, on their view, be regarded as accidental. Our theory, on the other hand, implies that the white dwarfs form a separate and detached colony; they ought all to be rather like one another, and there should be no continuity with ordinary stars. As regards their evolution, the white dwarfs have been described as the oldest stars extant, "vestiges of an earlier creation," and so on. Our view of their evolution implies that they are neither older nor younger than the great majority of stars; they have merely been more unfortunate. The white dwarf state is a sort of bankruptcy court into which a star falls when it is unable to make both ends meet in the matter of radiation. When the original Sirius broke up into Sirius *b* and Sirius *f*, the former contrived to keep most of the matter which was easily transformable into radiation, hence the present splendour of Sirius *b* and the unhappy condition of Sirius *f*. In such cases as α Centauri and Kruger 60 there appears to have been a fairer division of radiation-producing material.

III. The typical evolutionary path PQR in our diagram penetrates regions near Q in which no stars are found. A star at Q would have practically all its atoms stripped bare of electrons, while calculations on actual stars show that very few have more than about 95 per cent. stripped bare. (The slant lines in the diagram show the proportion of bare nuclei calculated for an assumed atomic number 20.) The obvious interpretation of the observed facts is that in some way the evolutionary paths are turned before they reach regions of, say, 99 per cent. of nudity.

If the annihilation of matter is a quantum process

of the kind I originally conjectured (NATURE, December 6, 1924) this would happen automatically, for the baring of each nucleus would represent a loss of energy-generating power, and a star with all, or too many, of its nuclei stripped bare would leave off generating energy until sufficient atoms had re-formed. The typical evolutionary path in our diagram must no longer be taken to be PQR , but some such path as $PQ'R$.

The belt of configurations in which, say, from 80 to 99 per cent. of the nuclei are bare forms a sort of common envelope to most of the evolutionary tracks in the diagram. There ought then to be a great concentration of stars in this belt. This is in agreement with what is observed, for the calculated position of the belt, as shown in our diagram, coincides very closely with that of the main sequence of Eddington and Hertzsprung, which, besides forming a boundary in the direction of high temperature, is conspicuous for its great concentration of stars.

IV. It can be shown (*Monthly Notices, R.A.S.*, June 1925) that when a star breaks into two by fission, each constituent must assume a higher temperature than the original temperature of the parent star. The increase of temperature is generally sufficient to throw both constituents into the main sequence, after which the loss of energy-generating power will, as already explained, prevent their becoming still hotter. This explains why both constituents of newly formed binaries are generally found to lie in the main sequence.

A star such as Antares (No. 1 in Fig. 1) may reach the main sequence by travelling along a normal evolutionary path such as PQ' for about a million million years, or, in the event of fission occurring, may jump to it almost instantaneously, forming a binary star such as V Puppis (No. 7 in Fig. 1).

V. The stars in the region of P in our diagram are red giants of enormous size and very low density; they are almost all variable stars. Mathematical analysis shows that stars in this region may be affected by a special type of instability, not so far mentioned. This would show itself in a tendency to develop pulsations of practically unlimited amplitude, and there appears to be some prospect of explaining long-period variability in this way. The short-period variables and the Cepheids may possibly be stars actually in process of fission, as is suggested by their position in the diagram. Such conjectures need to be tested very thoroughly before they can be accepted, but it is at least clear that the proposed theory of evolution provides a place quite naturally for these two main types of a stellar variation.

Each of the foregoing modifications of the simple theory has been demanded by theoretical considerations, and each has been found to provide a natural, and almost inevitable, explanation of one outstanding feature of observational astronomy, as follows:

- I. Giant and dwarf stars.
- II. White dwarfs.
- III. The "main-sequence."
- IV. Early spectral types of newly-formed binaries.
- V. Variable stars (conjectural).

It seems fair to say that no other theory of evolution gives a tenable explanation of even any one of these five features. This is the case for the proposed theory.

If a star, in breaking up by fission, divided its different ingredients proportionally between its two constituents, it is easily shown (*Monthly Notices, R.A.S.*, June 1925) that the fainter constituent would be of earlier spectral type than the brighter. This arrangement prevails in many newly formed binaries, but not in all (cf. Leonard, *L.O.B.* 343, 1923), and it is clear that in many cases, as in that of Sirius already discussed, the more massive constituent must have kept an undue share of highly radiating material; an extreme case of this kind is provided by the sun and earth. The situation is consistent with the supposition that the highly radiating material is of exceptionally high atomic weight and is therefore left in the more massive star when the lighter one is formed by drawing off the outer layers of the original star. Newly created matter probably contains elements of

atomic weights far higher than any known on earth; it may even consist entirely of such elements. Our terrestrial elements are merely a residue of material which is practically non-transformable—dead ashes for the most part, although possibly the radioactive elements still retain some vestige of the powers of primeval matter. For one brief moment it seemed possible that cosmogony might teach us how to obtain almost boundless supplies of energy by the annihilation of quite insignificant fragments of matter, but this apparently is not to be. So far as we can at present see, Nature has arranged that the energy-producing elements shall be kept out of the reach of man; while he may watch the process of transformation going on in the stars, he will never be allowed to operate it himself. Whether this is to his advantage or disadvantage, who shall say?

The Relative Age of Rocks containing Fossils.

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DURING recent controversies as to the evidence for the evolution of life in past ages, it has been stated that geologists arrange the fossil-bearing rocks in a "purely artificial" manner, not necessarily in the order in which they are found superposed. It has even been asserted that when the fossils occur in successive layers in an order which an evolutionist would say is the reverse of that expected, the rocks are assumed from this criterion alone to have been disturbed and turned upside down. The progressive development of life which a geologist recognises, indeed, is said to be imaginary and not proved by the observed order of superposition of the rocks.

Such statements are based on a complete misunderstanding of the facts. The science of geology originated, and the order of nearly all the principal layers of sedimentary rocks was first determined, on the unstable western edge of the continent of Europe. In this region from the beginning of geological time there have been frequently repeated downward and upward movements leaving records in sediments of the successive seas which overflowed and retreated. The sedimentary rocks have been tilted and their edges worn away in such a manner that their order, or relative age, is easily observed. Their succession in fact is so clear that it has been possible in several cases to follow the changes of material in one and the same layer—the sands and gravels which were deposited near the shore, the mud farther out, and the remains of calcareous skeletons forming limestone in the clear water of the open sea. As an illustration may be mentioned the lower Carboniferous deposits, which are open sea limestones in central England but gradually pass into estuarine sands and clays with beds of coal in the south of Scotland, where there are only occasional beds of limestone containing approximately the same fossils as the great marine deposits farther south. More than a century ago, when almost all naturalists believed in "special creation" and there were no accepted theories as to the order of "creation," the succession of the rocks in England and Wales was made out by William Smith from actual observation of their superposition. Later geologists merely elaborated

details, and made more extensive collections of fossils. Geologists on the present European continent found the same general succession in their several countries, only varied by local circumstances; some additional layers being intercalated in the typical British series, others omitted, and some being represented by different rocks. Allowing for the differences in sediment and its amount which would be deposited in different parts of the same sea and adjacent estuaries, the succession was discovered quite clearly by observations in the field.

It was not until the field-work was far advanced that the fossils were studied in detail and found to indicate distinct progress in the development of life on the earth. None but animals without a backbone have ever been found in the oldest fossiliferous rocks; fishes are known to have flourished long before any lung-breathing backboned animals; the cold-blooded amphibians and reptiles came successively before the warm-blooded birds and mammals; man appeared at the end. In several groups, too, fossils collected from rocks of which the relative age is definitely known from observation of the layers in the field, show that the lower grades appeared before the higher grades. This became evident so long ago as 1836, when Buckland in his *Bridgewater Treatise* remarked on the interest of the oldest known mammals from the Stonesfield Slate of Oxfordshire as belonging to the lowly pouched group of marsupials. He stated that "the analogies afforded by the occurrence of the more simple forms of other classes of animals in the earlier geological deposits would lead us to expect also that the first forms of Mammalia would have been marsupial."

When geologists began to study the marine fossil-bearing rocks in other parts of the world, especially North America, they discovered differences in detail, as might have been expected—differences both in sediment and in fossils. In all cases, however, where the order of superposition of the layers could be clearly observed, the succession of the various groups of fossils was proved to be essentially the same as in western Europe. Rocks containing approximately the same fossils in widely separated regions may not have been contemporaneous in formation; judging by the