Liquid Stars.

By J. H. JEANS, Sec. R.S.

THE view that the stars are gaseous structures has held the field for more than half a century; it is implied in Helmholtz's famous 'contraction-theory' of the source of solar energy as well as in the pioneer researches of Homer Lane. Emden, surveying the subject in his "Gaskugeln," scarcely discussed any alternative possibility, although finding that the centres of the stars must be too dense for the ordinary gaseous state to be possible. This particular contradiction disappeared, and indeed the whole question assumed a new aspect, in the light of a concept I put forward in 1917, according to which the atoms in stellar interiors were in a state of extreme electronic dissociation. For, as Eddington afterwards pointed out, electrons and atomic nuclei are of such diminutive size that if these, and these alone, form the flying units of a quasi-gas, no density observed in astronomy is too high to be compatible with the gaseous state.

In the ten years which have elapsed since I first propounded this view of stellar interiors, much labour has been devoted, particularly by Eddington but also by many others, to investigating the build and properties of the stars on the hypothesis that the flying units are too small to interfere appreciably with one another's motion—on the assumption, in brief, that stellar matter behaves like a perfect gas. As the central temperatures of the stars can be calculated with some accuracy, it might seem a simple matter to estimate the extent to which these temperatures would break up the atoms, and thus to decide whether the gas-laws would be obeyed or not. It is simple if the atomic weight of the atoms is known, but not otherwise; a temperature of 100,000 degrees will break up hydrogen completely, while one of 100,000,000 degrees fails to do the same with uranium. Eddington's discussions usually assumed atomic weights of 40 or 50, and with such atomic weights the atoms would be completely pulverised; on the other hand, with atomic weights five times higher, enough atomic structure would be left to cause the gas-laws to fail, although our ignorance of the effective sizes of highly ionised atoms makes it difficult to estimate the extent of this failure.

The hypothesis that the gas-laws are obeyed has proved disappointing, its consequences obstinately refusing to fit observed facts, and the hypothesis appears to be ripe for abandonment. Eddington and myself have independently investigated the relation which would connect a star's luminosity with its mass and diameter on this hypothesis, and actual stars are all found to be substantially too faint. To put the same thing in another way, if the gas-laws were obeyed in stellar interiors, stellar diameters would be far greater than they actually are. My own latest calculations suggest that the discrepancy is probably represented by a factor of hundreds; Eddington, from different data and different assumptions, got a smaller factor, but even by giving the hypothesis all the benefits of every possible doubt, no one has succeeded in abolishing the discrepancy altogether; at the best a factor of about ten persists.

Further, I have recently shown that a star which behaved like a gas would be unstable, either dynamically or thermodynamically, or both. Some time ago Eddington and Russell found that such a star would be dynamically unstable unless its rate of generation of energy increased somewhat

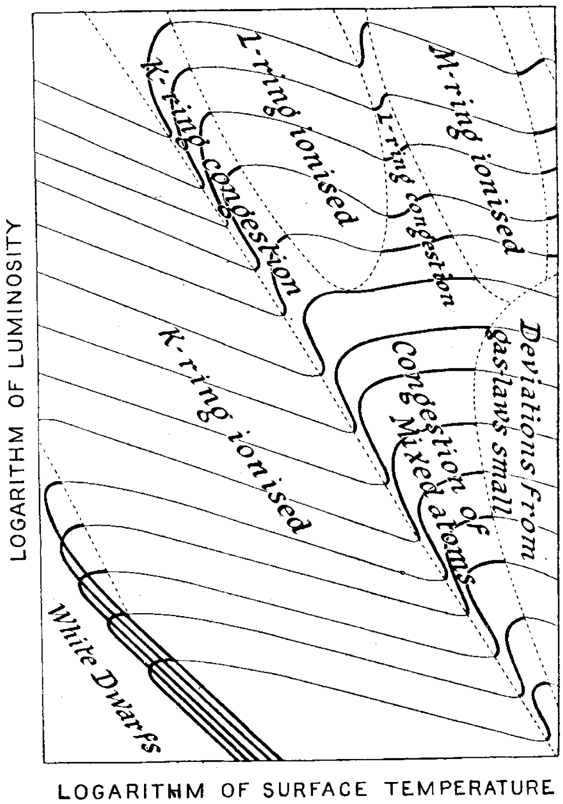

FIG. 1.—Theoretical diagram of stellar configurations predicted by the hypothesis of liquid stars.

rapidly as its temperature rose, but I have since shown that an adequate effect of this kind would render the star unstable thermodynamically; to keep our star dynamically stable, we have to endow it with precisely those properties which characterise an explosive at its flash-point. Thus a purely gaseous star must collapse dynamically, or explode thermodynamically, or both, according to the way in which its rate of generation of energy depends on its temperature; actual stars do neither.

Finally, direct evidence against the gaseous hypothesis is provided by binary stars which, to all appearances, have been formed by the break up of a single star which rotated too fast for safety. Fly-wheels and rotating masses of solid or liquid may break up in this way, but I have shown that a purely gaseous mass cannot; a mass of gas yields and expands, but can never break.

I have recently suggested (*Mon. Not. Roy. Ast. Soc.*, **87**, 400 and 720 ; 1927) that these various difficulties can be obviated, and a highly satisfactory agreement with observation secured, by supposing the central regions of a star to be liquid rather than gaseous, the outer layers of course remaining gaseous. In the quasi-liquid core the atoms are not completely broken up, retaining one, two, or even three rings of electrons, and as a consequence exerting about forty times the pressure they would if the gas-laws were obeyed. These deviations from the gas-laws secure the dynamical stability of the star, the nearly liquid core forming a firm unyielding base on which the outer layers of the star can rest in safety ; thermodynamical stability is ensured by supposing the star's liberation of energy to be of the 'radioactive' type, so that it is approximately uninfluenced by changes of temperature and density.

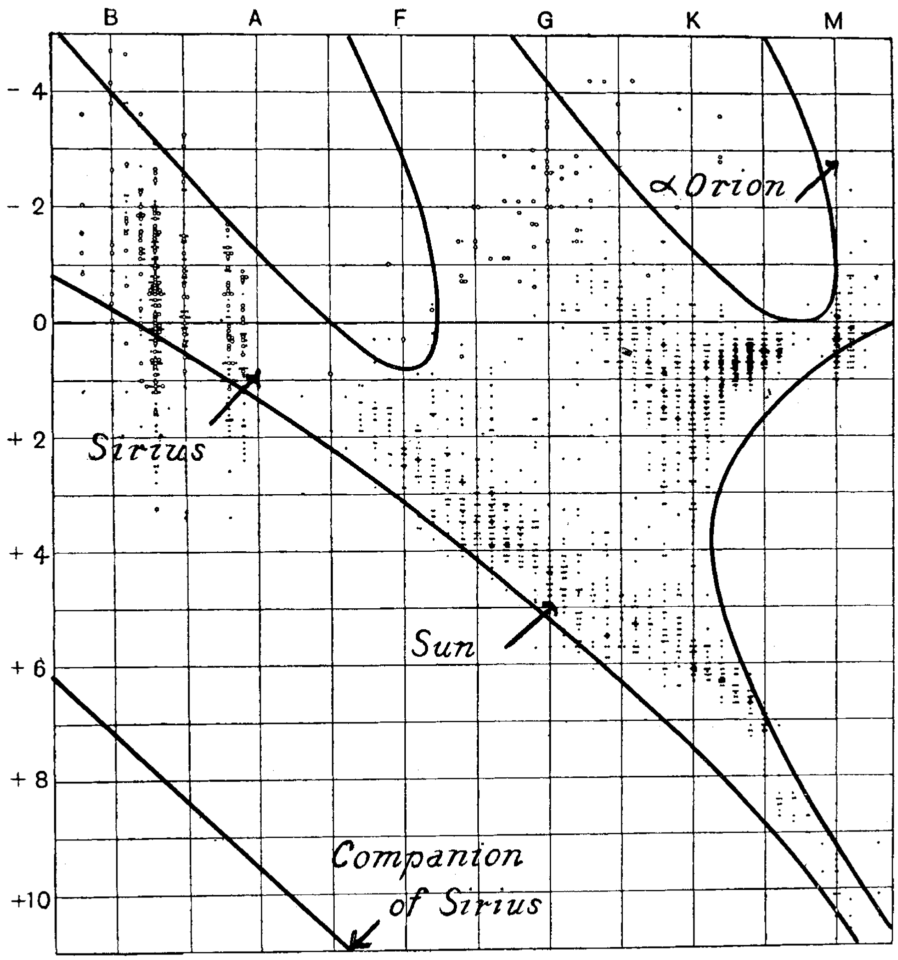

FIG. 2.—Diagram of observed stellar configurations (Mount Wilson Observatory).

Imagine a star starting from the low density with which it is born, and contracting through all its possible configurations of equilibrium. As its radius diminishes, its temperature rises as required by Lane's law, and this rise of temperature results in one ring of electrons after another being stripped from the atoms, so that the size of the atoms diminishes concurrently with that of the star. So long as the star is of low density, the gas laws are obeyed in its interior, but calculation shows that on the whole the star shrinks more rapidly than its atoms, so that in time states are reached in which the gas-laws are no longer obeyed. But while the star is shrinking steadily, its atoms shrink spasmodically as one ring of electrons after another is pulled off. If the stellar diameter is the tortoise, the atomic diameter is the hare ; its progress is by spurts and rests alternately. The spurts of the hare do not save it from ultimate defeat, but they result in its being alternately in front of and behind the tortoise. Detailed calculation shows that, as the star shrinks, the deviations from the gas-laws will not increase steadily but will fluctuate, being small just after each ring of electrons has been ionised, and becoming large just before the ionisation of the next ring. At these latter stages the atoms are jammed together, a substantial degree of jamming generally being necessary to secure the ionisation of the next ring. Such, at least, are the predictions of theory for massive stars. In stars of small mass, the fluctuations are smoothed out and disappear ; the hare goes with a steady gait, but is uniformly less rapid than the tortoise, at any rate until we come to the last ring of electrons, the k-ring. Here the hare makes a tremendous jump, and then has to stop since no further rings of electrons remain.

Fig. 1 shows the configurations which theory predicts to be possible for stars of different masses. The abscissa is the logarithm of the stars' surface-temperature, hot and therefore small stars being to the left ; the stars' diameter increases to the right. The ordinate is the logarithm of the stars' luminosity, bright stars being on top. Each continuous curve represents the theoretically possible configurations for a star of given mass, the curves for the most massive stars being on top. The fluctuations in these curves result from fluctuations in the extent of deviation from the gas-laws, and these in turn entail fluctuations of stability. Theory requires that those parts of the curve which are drawn thick shall represent stable configurations, all others being unstable. Thus if the hypothesis of liquid stars is true, stars ought to be observed to occur only in those parts of the diagram where the curves are drawn thick.

The background of Fig. 2, taken from the Report of Mount Wilson Observatory (1921), shows the observed distribution of 2100 stars; the thick lines are curves I have drawn to divide the diagram into regions occupied by, and avoided by, stars. The general agreement with the theoretical diagram shown in Fig. 1 is so good that we need scarcely hesitate to identify corresponding areas in the two diagrams.

The belt of stars which runs diagonally across the whole diagram is called the 'main-sequence'; it contains stars of ordinary radius, such as the sun, Sirius, and Procyon. In the stars which occupy the upper reaches of the main-sequence we see that the atoms are ionised down to their K-rings, but the less luminous stars such as the sun must contain all sorts of atoms mixed. Observation shows that the left-hand edge of this sequence is very clearly defined; the stars seem to press against it like flies against a window-pane. This sharp left-hand edge is determined by the condition that the atoms are jammed together almost as tightly as they can be packed; in the configurations there represented the density is the maximum possible, short of the final ionisation of the K-ring. The "white-dwarfs," such as the companion of Sirius, with diameters only about a fiftieth of that of the sun, and densities of about a hundred thousand times that of water, consist mainly of atoms stripped bare to their nuclei, although enough K-rings must survive to build up a firm liquid base at the centre of the star. Stars of huge diameter, such as Betelgeuse (α Orionis), with diameters hundreds of times that of the sun, and mean densities only about a thousandth that of atmospheric air, must have three rings of electrons (K, L, M) left on their atoms.

The upper part of the diagram forms a macrocosm of the atom itself, the great difference between the diameters of the nucleus and the k-ring being reflected particularly clearly in the big empty gulf between the white-dwarfs and the main-sequence. Thus the structure of the atom is blazoned across the heavens, and if the physicists had failed to unravel it, the astronomers might have succeeded—in time. Theory does not fix absolute values for the co-ordinates in Fig. 1 until the atomic weights and atomic numbers of the atoms are given. I have found that the best agreement with the observational material shown in Fig. 2 is secured by taking the atomic number to be about 94. Atoms of lower atomic number would lose their electrons at too low temperatures, while those of higher atomic numbers would grip them too tightly. Thus the main mass of the central liquid regions of the stars appears to consist of a sort of "supra-radioactive" atoms, with atomic numbers just above those of the ordinary radioactive elements such as radium (88) and uranium (92). We are driven back to Newton's conception of the stars as being formed of a special 'lucid' type of matter, and this lucid matter appears to come next in complexity after our terrestrial semi-lucid radioactive elements, of which the lucid elements may well be the parents.

Power Alcohol in Australia.

By Prof. JOHN READ.

THE main sources of organic energy which are at present being utilised in Australia are black coal and brown coal. The Australian deposits of black coal form about 2·2 per cent. of the total coal reserves of the world, being thus only slightly less extênsive than the deposits of Great Britain. The chief deposits of black and brown coal occupy very favourable locations in New South Wales and Victoria, respectively; and, in addition, the eastern coastal zone of Australia (including Tasmania) affords considerable opportunities for the development of hydro-electric power. In comparison with Great Britain, therefore, Australia is well endowed with natural sources of energy. At present, however, both these countries are almost wholly dependent upon outside sources for their supplies of liquid fuels, particularly for fuels fulfilling the requirements of the internal combustion engine. A very similar state of affairs exists in South Africa and in various other parts of the Empire; so that a problem of wide significance and extreme economic importance is here manifest.

In Great Britain, as in Europe generally, a good deal of attention is being paid to the Bergius process and the low temperature distillation of coal. Any such investigations directed towards the economic manufacture of liquid fuels from black or brown coal are patently of considerable interest to Australia, particularly as the processes would also furnish lubricating oils. Climatically, however, Australia differs so widely from Great Britain and northern Europe that it is not surprising to find the Australian more disposed than the European to draw upon his lavish current supplies of solar energy and less inclined to encroach unduly upon his limited capital of 'fossil sunshine.' This tendency is noticeable in a report issued recently by the Council for Scientific and Industrial Research of the Commonwealth of Australia, entitled "The Possibilities of Power Alcohol and certain other Fuels in Australia" (*Bulletin* No. 33. By G. A. Cook. Melbourne, 1927). The Australian imports of petrol and other petroleum products are increasing rapidly, the value of imported petrol alone being more than £6,500,000 per annum at the present time. Such a position is characterised as "very unsatisfactory even in times of peace, but in times of emergency it becomes positively dangerous." In 1925, the Joint Parliamentary Committee on Public Accounts took evidence on all phases of the Australian liquid