III

THE CONSTITUTION AND EVOLUTION OF THE STARS

THE preceding lectures have, I hope, presented to you a picture—drawn rather in outline, owing to the limitations of time—of the stars as they are known at present, their dimensions, masses, densities, surface brightness, and the like. It remains to speak of what has been done to correlate these facts into a theory of the constitution of the stars, and their probable evolution and age.

What makes this problem tractable, in spite of the limitations imposed by the remoteness of the stars in space, and our ephemeral duration in time, is that we have to deal only with the simpler and more general properties of matter. The vast variety of the forms of rock and mountain depends upon the solidity of their materials; the still greater diversity of the forms of organic life is based on the presence of chemical compounds of great complexity—and neither of these conditions can exist at all in bodies as hot as even the coolest stars. In the stars all matter must be gaseous, and the laws of gases are among the simplest known to physics. Add to them the still more general laws that govern gravitation, radiation, and the structure of atoms, and we have the controlling factors in the evolution of the stars.

Considering a star, then, as a mass of gas, isolated in space, we notice first that it must be in internal equilibrium under its own gravitation. The weight of the overlying layers produces a pressure increasing steadily from the surface to the centre, which must at any point be balanced by the expansive tendency of the gas, arising from its high temperature. The temperature, too, is greatest at the centre, and decreases towards the surface. Hence, heat must flow continually through the star's substance, down the temperature gradient, till it escapes by radiation at the surface. The supply of heat must be kept up in some way; and one obvious process, as Helmholtz suggested long ago, is the slow contraction of the star. The work done by the gravitational forces in pulling the outer parts of the star toward the centre, reappears as heat produced by the compression, and maintains the star as a going concern. As the star contracts, its density must increase; and the pressure will increase too, for the various parts of the mass are nearer one another, and attract one another more strongly. When the star has shrunk to half its original diameter, the mean density will be eight times as great.

If the star, after contraction, continues to be "built on the same model," so to speak—that is, if the law according to which the density increases proportionally toward the centre remains the same, except for the altered scale of miles provided by the shortened radius, the density at any point, after contraction, will also be eight times the original density at the corresponding point (distant from the centre by the same fraction of the radius).

How will the pressures at the two points compare? The portion of the star nearer the centre than the point under consideration is compressed by the weight of the overlying portions. After the contraction, every part of these is twice as near the centre as before, and will, therefore, be attracted four times more strongly. The whole compressive force will, therefore, be four times as great as at first; but the area over which this force is distributed will have shrunk to one-fourth of its former amount. Hence the pressure per unit of area will increase sixteen-fold, as against an eight-fold increase of density. Applying the familiar laws of gases, we find that the temperature of the gas, after contraction, must be twice its original value in order that equilibrium shall still exist when the star has shrunk to half its former size. More generally, during the whole process of contraction, the temperatures at corresponding points will be inversely proportional to the star's radius—so long, indeed, as the star continues to be built on the same model, and the simple gas laws hold good. This proportion was first proved by Lane of Washington, in 1870, and is known as Lane's Law.

It appears at first sight paradoxical that a star may grow hotter by losing heat; but the difficulty disappears when it is realized that the heat produced by the contraction exceeds the amount which is required to raise the temperature of the mass to the extent demanded by Lane's Law. The remainder is available for radiation, and it is only as it is gradually lost into space that the process of contraction can take place. The manner in which the surface temperature of a star, which determines its color and spectral type, will vary as it contracts is somewhat different. As has already been shown, the light from the far interior of a star stands no chance of getting out to the surface, but practically all of it will be scattered away by the gases through which it passes, and remain inside the star. Light can only reach us directly from a relatively shallow layer close to the surface, and it is a certain sort of average of the temperatures throughout this layer that gives the effective surface temperature. As the density of the star varies, the depth of this layer will alter, and in such a way that it always contains the same number of tons of material per square foot, since it is upon this quantity that the amount of scattering of light passing through the layer depends. As the star contracts, the total quantity of matter in this superficial radiating layer will therefore diminish proportionally to the surface area; that is, the radiating layer will form an ever decreasing part of the whole mass of the star, and its depth will be a smaller fraction of the star's radius. If the depth were a fixed fraction of the radius, we could apply the law of corresponding points and say that the temperature would vary inversely as the radius; but, in fact, after contraction the new radiating layer will form only the upper portion of the layer which "corresponds" to the old radiating layer, and its average temperature will be lower than that of the "corresponding" layer. On any reasonable assumptions regarding the way in which the temperature varies in the outer part of the star, it is found that the effective temperature of the surface will increase as it contracts, but much more slowly than the central temperature.

All these conclusions are based upon the fundamental assumption that the simple gas laws hold good throughout the star. This may safely be assumed if the density is low—say not more than twenty times that of air—but when the density begins to approach that of water, it will certainly be very far from the truth. As the density increases, the compressibility diminishes, so that, at the same temperature, it takes a greater increase of pressure to produce a further increase of density than would be necessary in a perfect gas. In other words, the material is better able than a perfect gas to stand up under pressure. Hence, referring to the argument by which Lane's Law was proved, we see that a smaller increase of temperature than is demanded by this law will enable it to meet the changing conditions resulting from contraction. Indeed, a point will in time be reached, when no further rise of temperature at all is needed, the decreased compressibility of the dense gas taking the whole load. Beyond this the increased pressure due to contraction acting alone will be insufficient to produce the necessary increase in density, and a fall in temperature must complete the adjustment.

We see, therefore, that a sphere of real gas, contracting under its own gravitation, will follow Lane's Law only while its density is small. As it contracts further its temperature will rise more slowly than this law indicates, reach a maximum, and then gradually diminish. During this long process, the model upon which the mass is built will itself gradually change—the increase of density toward the centre diminishing—but this will not alter the general character of the phenomena. We may at least say with confidence that the surface temperature, as well as that in the interior, will reach a maximum and then diminish, until at last the mass will shrink nearly to the greatest density which it can possibly attain, and end by cooling off almost like a solid body. During the early stages, while the temperature is rising, the body will be of large diameter. As it contracts its surface will diminish, but its surface brightness will increase, so that the amount of light which it gives out will not change much. It will, however, grow whiter as it gets hotter, until it reaches its maximum attainable temperature. By this time it will be much smaller in diameter than at the start, but only a little fainter. But after it begins to fall in temperature, while still contracting, the situation is different. There are now fewer square miles in its surface, and less light given out per square mile, so that its light will fall off rapidly, and it will grow fainter and redder until at last it disappears.

During its history, therefore, it will pass through any surface temperature lower than the maximum twice—once when of large diameter, low density, great luminosity and rising temperature, and again when its diameter is small, density high, luminosity low, and temperature falling. It is obvious that these contrasted groups of characteristics are exactly those which differentiate the giant and dwarf stars. The theoretical and observed pictures, indeed, agree not merely in their general outlines, but in every detail. For example, the lower the temperature selected for study, the greater will be the theoretical difference between the groups of stars of rising and falling temperature, and the greater is the actual difference between the giant and dwarf stars. The approximate equality in brightness among the giant stars of the various spectral classes, and the great differences among the dwarfs, find also a complete explanation.

Stars of large mass, as can easily be shown, should attain a greater maximum temperature than those whose mass is smaller, and should be more luminous than the latter, for the same surface temperature, especially in the giant stages. The great masses and luminosities of the B-stars are thus accounted for. The are not massive because they are hot, but hot because they are massive. Lesser masses never attain the B stage of temperature, but stop at A; and still smaller ones may not get beyond Class F, or even G. As we go down the spectral series, therefore, we are continually adding to our list stars of mass too small to get into any of our earlier groups at all—so it is no wonder that the average mass decreases for the redder stars. The fact that the masses of the giants average high, whatever their spectral type, is probably an effect of observational selection. We have picked then from a list of naked-eye stars, and hence from one in which the brighter stars have an egregious preference, and it has already been seen that, in these stages, great brightness means large mass.

A more searching test is found in the densities of stars of the various sorts; for here we can make our comparison quantitative instead of merely qualitative. The stars of increasing temperature should have densities at which the simple gas laws can be trusted to apply, at least approximately; the dwarfs should be so dense that we can be sure that these laws fail of application; while the hottest stars should have an intermediate density corresponding to the region in which the gas laws are strikingly at work. From a general knowledge of the properties of matter, we can say with certainty that a density less than ten times that of air falls in the first class, one greater than that of water in the second, while the "twilight zone" between corresponds to densities in the neighborhood of one-tenth to one-quarter that of water, and perhaps a little higher. Now we have already seen that the redder giant stars are less dense than air—the whiter ones being probably from ten to fifty times denser; that the average density of the A-stars is one-fifth that of the Sun, or one-third that of water, while their individual densities range from about fifty times that of air to that of water, and that the dwarf stars have densities running from about that of water up to four or five times as much. The agreement is perfect throughout, and there can be no remaining doubt that the proposed physical model represents what actually happens in the stars.

This theory of stellar evolution was first propounded by Sir Norman Lockyer who outlines clearly the physical processes involved. His criteria for distinguishing between stars of rising and falling temperature were spectroscopic, and chosen in a rather arbitrary way, with little explanation (though they were not very far from anticipating Adams' later discovery), and his views failed of general acceptance. It fell to the speaker's lot, some years later, to revive the theory, and point out the importance of the absolute magnitudes, which, indeed, furnish the key to the whole problem. This invaluable aid was not available when Lockyer began his work—for in those days little indeed was known of stellar parallaxes—so that it is not surprising that his individual assignments of stars to the classes of rising and falling temperature are often erroneous. With the wealth of material now available, it is an easy matter to point out stars in every successive stage of evolution, and to assign the large majority of those for which we have data to their place in its sequence. Mention should again be made, however, of the few, faint, but perplexing white stars of low luminosity. These do not fit into the scheme at all, and they present such an extraordinary combination of high temperature, small luminosity and considerable mass that it is very difficult to form any consistent idea of the physical conditions which exist on their surfaces. There are indeed more worlds for theory to conquer—and some of them look as if it would take hard fighting.

But there are other ways in which our knowledge of the properties of matter may be applied to the stars. A simple calculation shows that the gravitational pressure at the centre of the Sun must be something like a hundred million tons per square inch. The pressures in other dwarf stars are of the same order of magnitude. Those in giant stars are smaller, but are usually measurable in thousands of tons per square inch, even when the density cannot be many times greater than that of air. To withstand such a pressure, at this density, the gas must have a temperature of many millions of degrees.

What can we say of the properties which matter would exhibit at these temperatures? Twenty years ago, the only answer would have been, "Very little"; but now, with our knowledge of atomic structure, we can say a good deal. The extreme violence of the collisions between the atoms would knock off all the electrons of the outer shells, and keep them off. The lighter atoms—perhaps as far as sodium or even beyond—would lose all their electrons, and be reduced to bare nuclei. The heavier ones would retain their innermost one or two rings or shells of electrons, but lose the outer ones, which contain a considerable majority of the whole number of electrons originally present. We can be certain, however, that the nuclei themselves would emerge quite unscathed from these collisions, and that if an isolated nucleus, or the battered fragment of a heavier atom, had a brief interval of relative quiet, it would begin to pick up electrons again from those which passed by slowly enough, and to reconstitute the atomic structure. Could we remove a portion of the matter in this strange state and let it cool, the familiar atoms would thereupon rebuild themselves, bit by bit, and at the end they would be the same as ever.

The principal differences at the high temperature, from our present standpoint are: first, there would be a vast multitude of free electrons flying about, as well as the far heavier atomic nuclei, so that the average "molecular weight"—in determining which every free-moving particle in the gas counts as much as any other—would be much diminished. Secondly, the gas at this temperature would emit a tremendous flood of radiation, most of it of such short wave-length that it would resemble X-rays rather than ordinary light. This radiation would not go very far before it was scattered in all directions by the electrons, or absorbed in detaching some fast-knit electron from the remnant of an atom, only to be re-emitted when recombination took place. In either case the energy would be relayed back and forth from atom to atom, now in this direction, again in that, until in the lapse of ages it leaked gradually outward to the cooler parts of the star, on its way to the surface.

Jeans, was, I believe, the first to call attention to this extraordinary state of things, and Schwarzschild to point out the fundamental importance of the exchange of radiation in determining the conditions of equilibrium within a star; but the general solution of the problem came later, from Eddington, who was the first to appreciate one of its most fundamental features.

The flood of entrapped radiation, in its attempts to escape, exerts a pressure outward in all directions, just as a compressed gas would do. The existence of this radiation pressure was pointed out long ago by Maxwell's theory of light. With any light obtainable on Earth, even full sunlight, it is so minute that apparatus of the most delicate sort is required to indicate its existence; but at the temperatures which prevail inside the stars, it may amount (as Eddington pointed out) to hundreds of tons per square inch, and be an important factor in preventing the collapse of the star's interior under the weight of the outer parts. Indeed, under some conditions, it may do more than the gas-pressure due to the motions of the atoms and electrons, huge as the latter is. Following this lead, and working out the laws of flow of energy outward down the temperature gradient, he showed that certain simple and probable assumptions about the opacity of the medium led to the conclusion that, all through the star, the gravitational pressure would be proportional to the fourth power of the temperature, and that the shares of this pressure which were sustained by the gas-pressure and the radiation pressure would be everywhere in the same ratio. These conditions, combined with the law of gravitation and the gas laws, suffice to determine completely the model upon which the star is built, and to tell us practically all that we need to know about it.

For the case where the simple gas laws hold, the mathematical work had already been done by Emden, who found that the outer regions of the star were of very low density, while there was a rapid concentration toward the centre, where the density reaches fifty-four times the mean density. The central temperature of such a star obeys Lane's Law, while the surface brightness varies inversely in the square root of the radius. This means that the whole amount of energy radiated from the star's surface will be independent of its size—the increase in surface brightness and decrease in area, as it contracts, balancing one another exactly. The amount of the star's radiation depends upon the opacity of its material—diminishing as this increases—and is also proportional to the ratio which the radiation pressure bears to the total pressure at any part inside the star. This ratio increases rapidly with the star's mass, and the brightness should do the same.

These conclusions form a theory of giant stars. To extend it to dwarf stars Eddington repeated his calculations, taking into account the manner in which the comfirst mass of 10 grams, the next 100 grams, the third 1,000 grams, and so on. Then, by means of his equation, we find that the proportion which the radiation pressure bears to the whole will be quite negligible in all the spheres up to number 32, will increase rapidly for numbers 33 and 34; while for sphere 35 and all those beyond it the radiation pressure will be the dominant partner, leaving little for the gas-pressure to do.

Upon this long line of spheres, therefore, we find a small region in which a certain natural factor changes from an insignificant to a controlling role. On general physical principles, therefore, as Eddington puts it, we would expect "something to happen" in this critical interval, and "what happens is the stars." It is only when the radiation pressure and the gas pressure share the gravitational food that we get anything that can fairly be called a star. Smaller masses do not give out light enough to make them visible at interstellar distances, while the great ones, in which the radiation pressure is almost sufficient to counteract gravitation, would be in an almost unstable condition, so that a small disturbance, such as might be produced by a moderate rotation, would cause them to break up into parts. Hence smaller masses do not shine, and bigger ones break up, and only those in the critical intervening range of mass remain as luminous stars. We have seen that this should occur for masses comparable with those of spheres 33 and 34 of the series. Now the first of these is of half the mass of the Sun, and the second has five times the Sun's mass, so that the actual masses of the stars fall very exactly into the range indicated by the theory. Since the constants of this theory are derived from those which are the most fundamental in modern physics, we may truthfully say that the masses, and hence the sizes and brightness, of the stars are determined directly by the fundamental properties of the very atoms of which they are composed. It may be shown, for example, from Eddington's equation, that a mass of gas will shine as a giant star when, and only when, the ratio of the diameter of the star to the average distance between the atoms which compose it is about twenty times the ratio between the charge of an electron and the average mass of an atom (provided that this mass is measured, not in the ordinary way, but, as in the electrical case, by its power of attracting a similar mass at a given distance). The latter ratio is very large, about 4×10^{17}, so that the number of atoms in the star is enormous, and the star itself a very large mass.

One of the most impressive consequences of the whole theory is that the masses of the stars are determined by the interplay of the two forces, gravitation and radiation pressure, which, among all those in nature, are so feeble, under the conditions of ordinary experiment, that it taxes the skill of the experimenter to build an apparatus delicate enough to measure the effects of either one. Were we confined to experiments in enclosed laboratories, isolated in space, without the Earth's attraction to prove to us the existence of gravitation, it would probably have been long before the very existence of either of these forces would have been suspected; yet these forces, and these alone, when working on the grand scale, are powerful enough to shape the stars.

One question still remains. How long a time is required for this sequence of evolutionary changes? What is the life of a star? Here, again, the answer which we would now give depends upon knowledge which has come within the last decade or two. We have, even now, no direct evidence regarding the age of the stars, or the Sun; but we have information about the age of the Earth that has magnified our conception of the duration of the universe in time, in as startling a fashion as the study of the globular clusters has enlarged our idea of its extension in space.

The new method of measuring times is really very simple. Uranium is radioactive, and slowly "decays." One by one its atoms eject a part of their nuclei, and change into atoms of a different element. These again break up, and so on through a long and wonderful series of transformations, in which radium is one step. The particle ejected from the nucleus is sometimes an electron, but oftener an alpha particle, identical with the nucleus of a helium atom. Finally, at the end of the list, there remains a stable atom of lead—but not of ordinary lead, for its atomic weight is 206, instead of 207 as usual. In the course of ages, this radio-lead must accumulate in all uranium minerals. The rate of accumulation is accurately known, from a study of radio-active phenomena and we can be sure that the weight of lead produced in a millon years is 1/8000 of that of the uranium which is present. By determining the percentages of uranium and lead now present in a mineral, and applying this principle, we can find out how old the mineral is—provided, of course, that it contained no lead, when it was originally formed by crystallization in the molten rock mass. Such primitive lead would, however, be ordinary lead, of higher atomic weight, and a determination of the atomic weight of the lead derived from one specimen will enable us to tell how much of it was there when the mineral formed, and how much has been produced by radio-activity since this time.

In this way reliable values can be obtained for the ages of various minerals, and the dates of the eruption of the rocks in which they occur. The latter can often be defined in geological terms, and hence we can date the various geologic periods, finding a good general agreement with the geological order of succession. The oldest minerals so far studied are found in rocks of Middle Pre-Cambrian age. Specimens from Europe, Africa and America agree in giving ages of between a thousand and twelve hundred millions of years. These individual crystals have been in the rocks for all this time. The Earth, as a planet, must be older. The speaker, from consideration of the whole amount of uranium and lead in the Earth's crust, showed last year that its age is apparently less than eight billions of years, and probably something like four billions. If, as seems most probable, the planets were produced by eruptions from the Sun, under the tidal influence of a passing star, the Sun itself must have been already formed at that remote epoch.

But we may go further. Life already existed on the Earth in Pre-Cambrian times, and it is a moderate estimate to say that the process of organic evolution has lasted for a billion years. During all this time the Sun can never have been one stellar magnitude brighter or fainter than it is now, for in the first case, its heat would have raised the oceans to the boiling point, and in the second, they would have frozen solid—and either of these catastrophes would have put an end to evolution and to all terrestrial life. Now the Sun is a typical dwarf star, and there is good reason to believe that it is now well advanced in cooling and was once much brighter and hotter than it is now—of Class F, at least, though perhaps not of Class A. At such a time it must have been at least two magnitudes brighter than at present. Yet in the whole of geological time it has probably decreased half a magnitude or less.

We may, therefore, say, with considerable confidence, that the life of the Sun, and doubtless also of the stars in general, must extend over many billions of years.

But here we meet with a serious difficulty. We know the rate at which the Sun is radiating energy to the earth, and, from consideration of the way in which the Earth in turn radiates this energy into space, we can be sure that the Sun is also sending out an equal amount of heat into space in every direction. The total output is so great that it would exhaust the whole huge fund of energy, which would be made available by the Sun's contraction from an indefinitely extended size, in about twenty million years, as Lord Kelvin showed long ago. When we allow for the fact that some of this heat is still stored in the Sun's interior, and that it was probably much brighter in its earlier stages of evolution than at present, we see that, if gravitational energy alone was available as the source of its radiation, the Sun's past life as a star must have occupied but a very few million years. In view of the geological and radio-active evidence, there seems to be no escape from the conclusion that the Sun must have some other, and far greater, store of internal energy upon which to draw.

Further evidence in favor of this view has been found by Eddington in the behaviour of the star Delta Cephei. This is a typical giant star, about eight hundred times as bright as the Sun. Eddington has given good reason to believe that the cause of its variation in light is a periodic expansion and contraction of the whole star by about ten per cent. on each side of the mean. The period of this change would depend on the density of the star, and diminish if this increased. Hence, if the mean diameter was gradually contracting, the period should shorten. Eddington calculates that, if the radiation is supplied by gravitational contraction alone, the period should decrease by about forty seconds per year. The observations, which cover more than a century, show indeed a decrease of period, but at the rate of about a second in twelve years—five hundred times slower than the previous theory would demand. Here again we have evidence that the rate of stellar evolution—in a giant star this time—is many hundreds of times slower than it would be if there was not some internal store of energy to draw upon.

It is certain that no corresponding evolution of heat from any source occurs within the Earth, and we must therefore suppose that energy from the "unknown source" becomes available only at exceedingly high temperatures, such as prevail inside the stars. But if this is the case, and a star, in contracting, gets hot enough inside to start this process going, why does this not make the interior still hotter, and so cause a still more rapid transformation of the unknown energy into heat, till the process ends in an explosion on a colossal scale? I mulled over this idea for a couple of years before I saw the simple answer. If heat energy is supplied to the interior of a giant star, the star will have to expand, and if it expands, it must grow cooler. The process is the exact reverse of that by which contraction makes the star hotter, and at the same time compels the escape of heat from the surface into space. Hence, if too much heat is supplied from the unknown source, the star will expand and cool, shutting off farther supplies. It is easy to see that we have here a self-regulating process, which, in the long run, will automatically adjust the supply of heat in the interior so that it just makes up the loss due to leakage toward the surface and radiation into space. In the short run, we might find alternate over-production, leading to expansion of the star and cooling, and under-production, permitting contraction and heating; and oscillations of just this sort appear to happen in the Cepheid variables. Though the star may thus be kept shining for a very long time, it cannot go on forever, for the store of internal energy, however vast, must be finite, and will gradually be used up. As this happens, the star will contract, although very slowly, and ultimately pass through the various giant and dwarf stages, in substantially the manner which was described earlier.

Such a store of available energy will account for the facts; but how shall we attempt to account for the store of energy itself? One thing is clear at the start. The only places small enough to contain so huge an accumulation are the nuclei of the atoms. I say "small" advisedly, for it is only when the constituent parts of which the atoms are built come exceedingly close together that the forces between them can become great enough to account for their possession of such an amount of energy. Radio-active energy, which comes from atomic nuclei, represents indeed one such gigantic store. But the amount of energy which must once have been stored in each gram of the Sun's mass, to account for its past radiation of heat, is even greater than that contained in uranium. We cannot do more than guess where it may have been hidden; but one very recent piece of work affords a possible clue.

Aston, in one of the brilliant researches which we have learned to associate with the Cavandish Laboratory at Cambridge, has invented a beautiful apparatus which sorts atoms, by giving them electrical charges and shooting them through a vacuum under the influence of electric and magnetic fields. The resulting forces deflect atoms of different weights in different directions, and bring each kind to a separate focus upon a photographic plate, producing images when the plate is developed. By measuring these plates the atomic weights may be determined; and Aston has found that, in every case but one, the true atomic weights are exact integers, within the accuracy of measurement, which is about one part in a thousand. When the chemist finds an atomic weight which is not an integer, such as 35.46 for chlorine, this is really the average for two different kinds of atoms of the same chemical properties, but different weights, both of which are integers—35 and 37 in this case. The one exception is hydrogen, for which the chemist's determination 1.008 is exactly confirmed.

Now it is more than a century since Prout suggested that, since the atomic weights are so nearly integers, the atoms themselves are built up out of simple units. We now transfer this idea to the atomic nuclei, which contain practically all the mass, and Aston's beautiful researches practically compel belief. The hydrogen nucleus, or "proton," is the lightest of all, and we would naturally look to it as the fundamental unit. Rutherford's success in knocking the nuclei of elements such as oxygen, nitrogen and sodium to bits, by collision with fast moving alpha particles, has furnished a definite proof that protons, and alpha particles as well, are actual constituents of these nuclei. Many nuclei must also contain electrons, which prevent the net electric charge from getting too high. It looks, for example, as if an alpha particle was built of four protons and two electrons, held together by forces of whose nature we are ignorant. This would give exactly the right electric charge; but the mass of the four protons would be greater than that of the alpha particle by one part in 130. (The electrons weigh next to nothing.) This seems to spoil the explanation altogether, but an escape is found in that great resolver of otherwise intractable difficulties, the Principle of Relativity. According to this, all energy has mass, and all mass is equivalent to energy. The loss of mass in the formation of the alpha particle would mean that, in forming it, energy would be liberated, which would have to be put back into it again in order to separate the parts. The calculated amount of energy is so enormously great that it is not at all surprising that the alpha particle is so stable. Even in the collisions with other atomic nuclei which shatter the latter into fragments, the forces (which can be roughly calculated) are not nearly strong enough to disintegrate it.

We may now suppose that, in the interior of the stars, and by some process the details of which are still quite unknown, the atoms of hydrogen are taken apart, and the pieces—protons and electrons—built up into the nuclei of heavier atoms, with just enough electrons left over to build the outer parts of these. We cannot be sure, of course, that such a thing actually happens; but, if it does, the energy liberated will suffice for the present demands of astrophysics. If the Sun, for example, was originally all hydrogen, which was transformed in this fashion into other elements, the energy which would be set free as a by-product would keep it shining at the present rate for about 120 billions of years.

Such is our present conception of the stars, their distance, their age, their nature, and their life-history. In the grandeur of its sweep in space and time, and the beauty and simplicity of the relations which it discloses between the greatest and the smallest things of which we know, it reveals as perhaps nothing else does, the majesty of the Order about us which we call Nature, and, as I believe, of that Power behind the Order, of which it is but a passing shadow.

HENRY NORRIS RUSSELL.

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