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THE SOURCE OF SOLAR ENERGY[1]

INTRODUCTION

IT has been wisely said by Dr. W. W. Campbell that a scientist does not create the truth. He does nothing whatever to the truth; he simply uncovers it. Through the analysis of physical science, the universe is resolved into atoms—protons and electrons, and the cosmic laws are reduced to action and reaction of these integral parts. A general simplification has resulted; in the terms of atoms many complicated phenomena have been solved, and it is hoped that the new physics will shed some light on the problem in hand—the source of solar energy.

It is known that throughout entire geological time the sun has been radiating energy at a rate which has varied but little. With the generally accepted estimate of the age of the earth[2] each gram of the sun has accounted for about 2×10^9 calories, and the well-known problem arises: whence came this heat. The great quantity of the solar radiation and the inadequacy of the simpler theories to account for it have been so frequently discussed that a short review of them will suffice here.

It does not come within the scope of this paper to reexamine the data for determining the age of the earth. Estimates have ranged from 10^8 years to Russell's absolute maximum of 6×10^9. Since even the minimum value given above is far in excess of that demanded by the following theories it is not necessary for our present purpose to defend any specific value. For the sake of definiteness we adopt the value 10^9 as of the proper order of magnitude, especially since this figure has apparently met with wider acceptance than any other.

(1) ORIGINAL HEAT

The sun radiates about two ergs per second, or 1.5 calories per year, for each gram of its mass. The researches of Emden, Eddington, Jeans and others have shown that, in order to maintain the observed mean density of 1.4 against the enormous pressures existing in the far interior, a critical temperature of some 10,000,000° to 30,000,000° K is required. The opacity of the interior, by setting up a negative temperature gradient, reduces the temperature of the photospheric surface approximately to 6,000° K.

[1] Awarded the A. Cressy Morrison Prize in 1926 by the New York Academy of Sciences.

[2] 10^9 years.

The mechanism of the opacity is generally recognized to be the interaction of radiation and electrons with positive nuclei and highly ionized atoms in the center of the sun.

In spite of the great central temperature, it is immediately obvious that mere cooling is insufficient to account for the supply of the sun's heat. At the observed rate of radiation, and even assuming a maximum value for the specific heat, the lapse of a comparatively short period of time, say a million years, would certainly reduce the temperature so that the surface would be markedly cooler. The customary argument used in this connection is not valid. It has been said that since the average temperature of the sun falls at least one degree a year the surface would be sensibly cooler in even a few thousand years. The reduction of the central temperature by so small a fraction would scarcely disturb the temperature gradient. As far as historical time is concerned, the sun may well have been a hot body cooling according to the well-established laws of heat conduction. But when we take geological time into consideration the case is different. We must find some source of heat to augment the original supply. We shall consider in turn the various possible ways in which the energy may have originated.

(2) CHEMICAL

Under this heading are grouped the processes which deal with the liberation of heat by the chemical combination of two or more atoms. Combustion is a specific example, governed by the equation:

$$C + 2O = CO_2 + 2140 \text{ cal. per gm. of reacting substance,} \quad (1)$$

which is equivalent to saying that the energy in one gram of uncombined carbon and oxygen, mixed in the proportion of one atom of the former to two of the latter, exceeds that in one gram of carbon dioxide by 2,140 calories. In no case has the heat of any chemical reaction been found to exceed ten times the value in the above equation. In the past billion years each gram of the sun will have radiated 10^5 times as much heat as could possibly be generated chemically. It is immediately obvious that chemical activity contributes practically nothing to the total energy of the sun.

(3) GRAVITATION

(a) *Meteoric.* The discovery, by Rumford (1798) and Davy (1799), that heat has its mechanical equivalent in work, led to other theories regarding the source of solar energy. The first of these was Mayer's hypothesis that the radiation might be continually replenished by an incessant rain of meteoric matter upon the solar surface. It is easily shown that a piece of matter, falling from a great distance, would reach the sun with a velocity of some 6×10^7 cm./sec. Substituting in the well-known formula for the kinetic energy,

$$E = 1/2 \text{ m } v^2, \quad (2)$$

and, taking m equal to one gram, we get

$$E = 1.8 \times 10^{15} \text{ ergs} = 3.8 \times 10^7 \text{ calories}, \quad (3)$$

or about 20,000 times the heat produced by the complete combustion of a gram of carbon and oxygen, as shown above. The total annual radiation of about 3×10^{33} calories would, then, be equivalent to an influx of 8×10^{25} grams of meteors per year or 3.7 grams per square centimeter of surface per day.

Objections to this theory are many and serious. In the first place the density of meteoric matter in space, calculated from the frequency with which meteors are observed to strike the earth, is far too low to furnish even a fraction of the material required by the hypothesis. Furthermore, the increase of solar mass by such a process of accretion would produce corresponding accelerations in the movements of the planets, which could hardly have escaped detection and, finally, it is obvious that the heat produced by impact of solid matter on the solar surface would have a negligible influence on the steep internal temperature gradient. If, by any chance, the sun should happen to encounter during a given year the quantity of meteoric matter mentioned above, the life of the sun would not be lengthened in the least. Instead we would receive, during that year, twice the quantity of heat generally radiated by the sun.

(b) *Contraction.* Of all the theories of the origin of the solar heat, the one which has played the most prominent rôle is that put forth by Helmholtz in 1854. It, too, appeals to gravitation as a source of energy, but instead of the impact of exterior particles, it assumes a general contraction for the sun as a whole to renew the kinetic energy of the solar atoms. It is easily computed that a contraction of but one twentieth in the diameter of the sun per million years would generate enough heat to replenish that lost by radiation. Calculating backwards, we find that if the sun were originally an extended nebula, the average energy produced by contraction to its present state would be 27,000,000 calories per gram. Or, postulating the present rate of radiation as extending uniformly into the past, the minimum age we can derive for the sun, corresponding to an infinite initial radius, would be 18,000,000 years. This would be further reduced by considerations of the greater central density and the necessary discarding of the hypothesis of uniform radiation. The theory of Helmholtz thus fails in the same way as the other theories, in that it does not provide a sufficiently long geological history for the earth. Attractive and ingenious as the hypothesis is, it must, therefore, be discarded.

(4) RADIOACTIVE

Since certain elements which disintegrate with the liberation of enormous quantities of energy have been found, it is necessary to consider what contribution —if any—they make to the total solar radiation. Uranium, for example, undergoes the well-known series of radioactive transformations which finally, after the emission of numerous α, β, and γ rays, terminate in inert radio-lead.

Of the three classes of rays, the alpha variety (which is recognized to consist of helium nuclei ejected with high velocity from the radioactive nucleus), contributes by far the larger percentage of energy. A gram of uranium, in equilibrium with its products, would produce approximately three quarters of a calorie per year, considerably less, therefore, even for a sun made entirely of that element, than would be required to replace the heat lost by radiation.

Examining in turn all radioactive elements, we find that each must be discarded as inadequate. Radium, whose emissive power is about 10^6 times that of uranium, would be satisfactory only if its "half-life period" were not so short. Since the quantity of radium, however, is halved every 1,730 years, the radiation therefrom would have to vary correspondingly—contrary to observation.

(5) INTRA-ATOMIC

(a) *The Equivalence of Matter and Energy.* We are thus driven by a sort of reductio ad absurdum to consider a principle which has often been suggested on philosophical grounds, *viz.,* the equivalence of matter and energy. The success of the relativity theories, both special and general, render the adoption of this hypothesis less distasteful than it would have been say twenty years ago, and, what is extremely important, they provide a quantitative basis for calculation, according to the well known formulae

$$E = m\,c^2 \qquad (4)$$

where m is the mass in grams, c, the velocity of light, and E, the energy to which the given mass is equivalent. Numerically, substituting $m = 1$ and $c = 3 \times 10^{10}$ centimeters per second, we find that one gram of matter equals 9×10^{20}, or about 2×10^{13} calories.

(b) *Chemical and Physical Considerations.* The principle of equivalence has been rendered more probable by its successful application to atomic phenomena, *e.g.,* the fine structure of the spectral lines of hydrogen. Furthermore, the revival of the Prout hypothesis in a somewhat altered form seems to demand it. If 4.032 grams of hydrogen may conceivably be put together in such a way as to make 4.000 grams of helium, we have to postulate the loss of 0.032 grams of mass, or, from the foregoing formula, 6.4×10^{11} calories. Writing this in the customary form, we have

$$4\ H = He + 1.6 \times 10^{11}\ \text{cal.} \qquad (5)$$

calculated, as in equation (1), per gram of reacting material. The above equation signifies that if hydrogen can be transformed into helium, energy of the order of 10^7 times that produced in an ordinary chemical reaction would be liberated. Herein we find an explanation for the extreme stability of the helium nucleus or α-particle. The most rapidly moving of these have initial velocities of approximately 2×10^9 centimeters per second. Their kinetic energy,

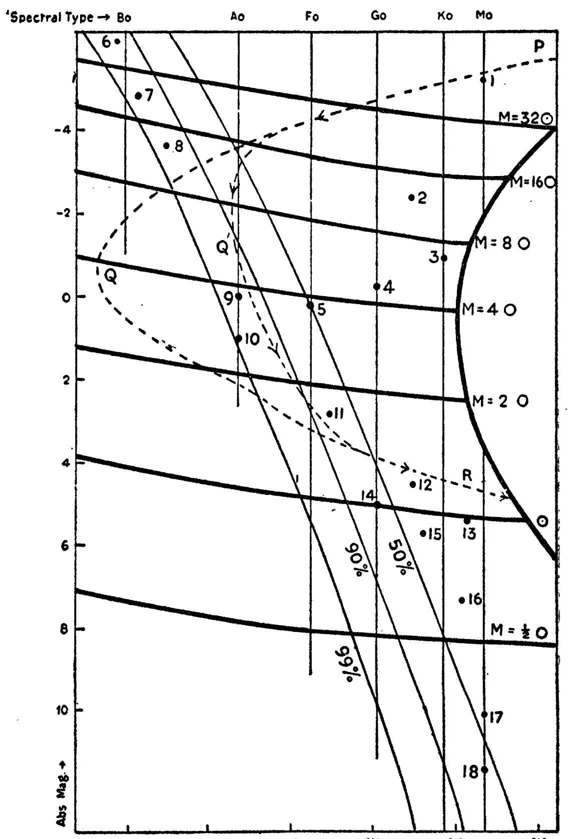

FIG. 1.—The stars, which are those shown by Russell in his diagram in NATURE (August 8, 1925), are as follows: 1, Antares; 2, δ Cephei; 3, Arcturus; 4, 5, Capella; 6, Plaskett's star; 7, V Puppis; 8, Y Cygni; 9, β Aurigæ; 10, Sirius; 11, Procyon; 12, 13, α Centauri; 14, Sun; 15, 16, ξ Bootis; 17, 18,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

on a gram basis, from formula (2), equals 5×10^{10} calories, or, as will be seen by comparing with equation (5), less than one third the amount necessary to disrupt the nucleus in a collision.

(c) *Stellar Evolution.* Before going further into detail we shall first develop some preliminary considerations. Any theory which applies to the sun must also be applicable to the stars in general and, conversely, it is not improbable that we may find the solution of our problem in a study of stellar statistics. The stages of growth of the present stellar evolutionary theories are so well known that we shall refer to them only briefly. Paramount, was Russell's discovery that the surface temperature and total intrinsic brightness were not entirely independent of one another. Their statistical relationship is shown in the famous giant-dwarf diagram. (See Figs. 1 and 3.)

Eddington's discovery[3] that the luminosity of a star is apparently governed by its mass changed many of our preconceived ideas regarding stellar evolution. His findings are summarized in Fig. 2. It is significant that the stars which we have always regarded as the oldest are the least massive. Here, at last, is important confirmation of our annihilation theory. In fact, the observed evidence seems to demand that the star decrease in mass during its life history.

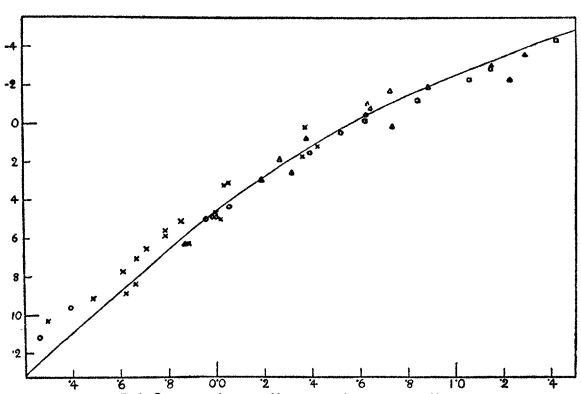

Fig 2.—Ordinates—Absolute Magnitude. Abscissae—Log Mass
O First Class. X Second Class. ☐ Cepheids Δ Eclipsing Variables.

(d) *Stellar Evolution and the Annihilation of Matter.* The atomic condensation of hydrogen into helium, as hitherto explained, does not permit of sufficient variation in mass and must be discarded. It has been suggested by Russell[4] that the heat-forming process may consist of the collision and coalescence of a proton and an electron, the neutralization of the charge permitting the disappearance of mass and its reappearance as energy. This theory, too, has its difficulties, for it would make the transformation dependent upon and favored by high temperature and high pressure. Thus, in the center of the dwarf stars, where we meet with these conditions, the rate of energy production should be greater than in the giant stars, the reverse of the actual case. Eddington has given an excellent summary of the problem.[5]

Jeans's criticism, which applies to any theory making the evolution of energy dependent upon temperature and pressure, is, I think, well founded. The proponents of those theories rely on the adiabatic qualities of the star to maintain equilibrium—*i.e.,* when too much heat is generated they assume an expansion and resultant cooling to "turn off" the supply. It is difficult to see how the star could expand rapidly enough to neutralize the increased rate of production due to the already too rapid emission of energy. Jeans has compared the material to gunpowder and predicts an explosion. Owing to its inertia, the star could hardly compete with the speed of atomic processes.

Eddington attributes the lesser radiation in dwarfs to their greater age, *i.e.,* the transformable material is approaching exhaustion, leaving only the inert elements. He thus apparently agrees with Jeans, who has remarked that ordinary terrestrial atoms, with the exception of the radioactive series, do not show any disposition to be transformed. Furthermore, both Eddington and Russell are extremely indefinite as to their nature of the energy-giving matter. If it is not composed of atoms or their derivatives, what is left? If we need the inert terrestrial type of atoms to dilute the decomposable material, only the radioactive atoms remain to be considered, and radioactivity is a transformation which takes place, as far as we know, almost independently of temperature and pressure. We are led, by a natural process of reasoning, to consider the work of Jeans.

(e) *"Super-Radioactivity."* Jeans has postulated that the energy originates in a sort of super-radioactivity. Eddington's mass-luminosity relation may then be interpreted in a slightly different manner. It has been stated earlier in this paper that the sun radiates 1.5 calories per year per gram of its mass. Among the stars we find that this figure varies considerably from stars like the giant, Canopus, which is generating energy at about five hundred times the solar rate, to dwarfs, like Krueger 60, where the quantity is a hundred times less than the sun or to Sirius B, the white dwarf, which is still smaller by a factor of approximately three.

As far as the radioactive elements go, Jeans points out that we have on our earth a very poor sample

[3] *M.N.* 84 308, 1924.

[4] *Pub. A. S. P.* 31 1, 1919.

[5] *Nat.* **117**, May 1, 1926, supplement.

of the universe. The material which comprises our planet came from the outermost layers of the sun, where the generation of energy is already small. If there are, as Jeans postulates,[6] elements of higher atomic weight than uranium, by far the greater amount would, in the absence of convective stirring, sink into the central portion of the sun. It has often been said that there is, apparently, no real reason why such elements should not exist. It is possible, however, that nature has provided a limit. As we pass to the more complex elements we find the nucleus continually increasing and the innermost electronic orbits decreasing in size. Rosseland[7] has pointed out that, for uranium, the radii of the orbit and the nucleus are of the same order of magnitude. He hints that radioactivity may result from the interaction of the two mutual forces. On this theory, radioactivity for elements beyond uranium, where the orbital electrons may actually penetrate the nucleus, would be much greater and it is not impossible that the transformation of matter into energy with the subsequent breaking down into less complex elements would result. By thus assuming that the radiation is liberated independently of temperature and pressure, we avoid the difficulties mentioned in the foregoing sections.

The mutual annihilation of a proton and an electron should result in the birth of a quantum of energy, of wave-length 1.3×10^{-13} cm. In the center of a star, this radiation would be transformed into longer wave-lengths by the various forces acting—Compton effect, atomic absorption and emission, scattering, etc. In Nebulae, however, where the opacity is much less, the quanta would escape practically unchanged. The fact that Millikan has recently proved the existence of highly penetrating radiation of approximately this wave-length—the intensity of which is apparently uniform night and day—is important observational proof that some process similar to that which we have described is occurring out in space.

Jeans has shown that the increase in average atomic weight as we near the center of a star, which would be the necessary outcome of the presence of the "super-radioactive" elements, tends to clear away the existing discrepancy in the coefficient of stellar opacity.[8]

Turning again to Fig. 1, which is given by Jeans,[9] we find plotted, in the customary manner, absolute magnitude against spectral type (log T). He employs his equation for stellar equilibrium, assuming a mass and surface temperature for the star in order to compute the absolute magnitude. Curves are drawn, the heavy lines slanting upward toward the left, to represent the stable configurations. When two of the quantities are given, the third may be fixed from the diagram. The curved line on the right marks the boundary between stable and unstable configurations—between positive and negative values of the stellar opacity.

A star whose representative point might fall within this negative region would be radiating energy faster than it could produce it. Equilibrium would now be impossible and the star would draw upon its internal gravitational supply, contracting rapidly. Eddington has shown that, since the gas molecules in the center of the star are free electrons, atomic nuclei and atoms ionized to the innermost orbits, very great densities are permissible. The star would contract until the ionized atoms were packed so tightly together that Boyle's law no longer holds; finally joining that class of stars known as "white dwarfs."

In Fig. 1, the slant lines represent the state of ionization in the stellar interior, calculated for an atomic weight of 20. On the simple theory, the course P Q R would be a typical evolutionary path which might be taken by the star. It may be significant, however, that no stars are observed which fall into the region Q, which represents atoms completely stripped of electrons. This suggests that the atomic processes stop when the nuclei approach nudity, as would be the case if radioactivity depends upon the penetrating of planetary electrons. The observed path, then, will be warped to the shape P Q′ R.

(f) *Double Stars.* It has long been recognized that double stars are formed by fission. We have had some difficulty in accounting for the observed fact that the newly formed spectroscopic binaries are of early spectral type, as established by Campbell, long ago. It is a signal triumph for Jeans's theory of stellar energy that it explains very clearly exactly why this condition exists.

The curves in Fig. 1 are drawn with sufficient accuracy to demonstrate the order of magnitude of the effect. To make the example concrete, let us suppose that a K0 star of mass four times that of the sun breaks up into two exactly similar masses. The brightness of each component will now be one half that of the original star, or 0.75 magnitudes less. Since the absolute magnitude of the parent star was 0.2, we now consult the diagram to determine the equilibrium configuration for a star of the required mass (2 ☉) and absolute magnitude +1. The figure

[6] Papers in *M.N.*, 1925 and 1926.

[7] *Nature* **111**, 357, 1923.

[8] *M.N.* **86**, 561, 1926.

[9] *Nat.* **111**, 19, 1926.

clearly shows that the stars resulting from the fission would be of spectral type earlier than BO.

The complete theory[10] takes account of the case of unequal fission. Jeans has shown that, in this event, the more massive constituent is to be the brighter and of earlier spectral type, in complete agreement with the observations of Shapley.[11] Reversing the process, we may calculate, from the present condition of the binaries, the state just before the fission occurred. We find that they occupied a position somewhere in the region of the long-period and Cepheid Variables, suggesting that these stars may be binaries in the making.

The realm of visual binaries furnishes additional data which seem to be consistent with the theory of Jeans. The only white dwarf stars known are components of binaries. While this may be attributed to the fact that their dwarf character is emphasized by association with a second star, the theory of energy now under consideration suggests the probability that they are the direct product of extremely unequal division of the heat-producing material.

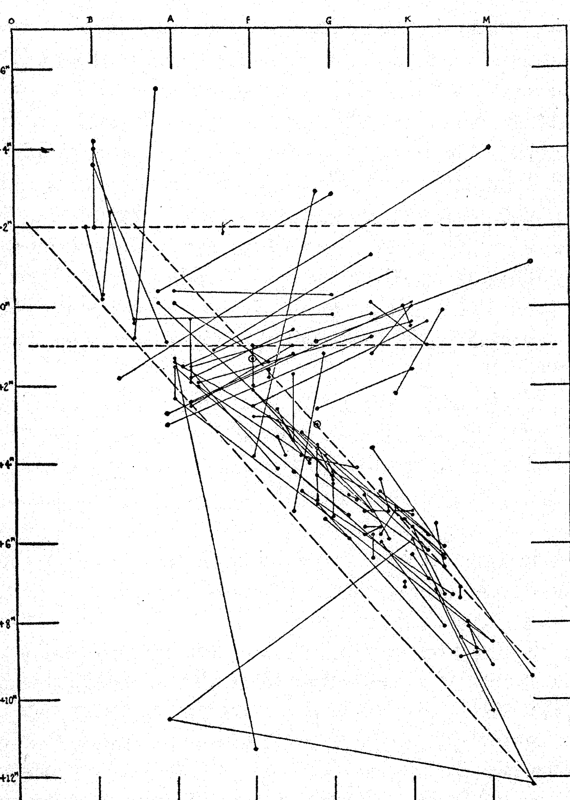

FIG. 3.—Spectral Classes and Absolute Magnitudes of the Components of 85 Visual Binaries.

[10] *M.N.* 85, 800, 1925.

[11] "A Study of the Orbits of Eclipsing Binaries," *Princeton Contributions*, No. 3, 1915.

Hence the splendor of Sirius A and the faintness of Sirius B.

Leonard[12] has investigated the statistics of the visual binaries. From eighty-five double stars of known spectra and parallax, he has plotted the data in the customary manner; the components are connected by a straight line. His diagram is reproduced in Fig. 3. It will be noticed, especially in the giant sequence, that the fainter component is, in general, considerably less bright than the average star of its spectral type. Among the dwarfs the discrepancy is not as marked.

I have examined the visual binaries given in the Harvard list[13] for a similar relationship. Seares[14] has given a curve for the maximum frequency of the stars (not in binaries) for the various spectral types. If the components of a given binary are average stars, the difference in magnitude can be predicted from Seares's curve[15] if their spectral types are known. This difference can be compared with the observed value. Calling the first $\triangle$ m and the second $\triangle$ m′, then $\triangle$ m′–$\triangle$ m will be a measure of the deviation from normality.

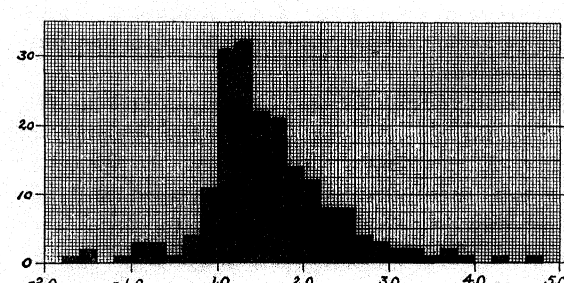

FIG. 4.—Ordinates—Number of Binaries Abscissae—$\triangle$ m′—$\triangle$ m.

The result of the investigation is presented in Fig. 4, which shows the frequency distribution of $\triangle$ m′ – $\triangle$ m for each two tenths of a magnitude. I have excluded from the diagram all optical doubles and binaries where one component was obviously a giant of type earlier than G0 and later than A5. This latter step was necessary in view of the great dispersion of absolute magnitude among the giant F stars. Fig. 4 exhibits a distinct asymmetry, plus values being far in excess of the negative. The result may reasonably be taken to mean that the brighter component of a binary has a higher and the fainter component a lower absolute magnitude than the average stars of their spectral classes. While it is far from proved that all binaries have originated by

[12] *L.O.B.* No. 343, 1923.

[13] *H.A.* 56, No. 7.

[14] *M.W. Contributions* No. 226, 1921.

[15] *Op. cit.* Fig. 1.

fission, it is generally believed that the components have a common origin. The statistical relationship shown in the diagram is interesting, though I do not wish to emphasize any particular interpretation. A similar investigation of the more accurate but less extensive data published in Leonard's paper[16] confirms the preliminary results; the corresponding diagrams differ scarcely at all. The selection of the material is such that extremely faint components, such as Sirius B, are excluded because of the difficulty in securing their spectra. Including these cases would probably tend to increase rather than decrease the observed discrepancy.

On the new intra-atomic theories, the life history of a star is considerably lengthened, to the order of 10^{13} years. It has been demonstrated that the orbital diameters and eccentricities of the original spectroscopic binaries could not have changed sufficiently in the short time allowed by the older theories to account for the existence of visual binaries. The new extension of the time scale, however, as Jeans has shown,[17] allows a sufficient number of long-range encounters with other stars to produce the observed result.

(g) *Objections to the Theory of Jeans.* Eddington has criticized Jeans on the grounds that his theory makes the rate of generation independent of the total mass of the star, which is, at first sight, contrary to the observed mass-luminosity relation. The objection, is, however, not well founded, for it is obvious that if we arrange the stars in order of increasing mass we shall find them also arranged approximately in the order of increasing generation of energy per unit mass. One does not necessarily cause the other. They are both the result of the stars having been arranged in order of age. If all the stars at birth had identical masses, they would form statistically some such distribution as the mass-luminosity law. A glance at Fig. 2 will suffice to show that there is sufficient dispersion in the observed stellar luminosities to allow for a wide enough variation in the original mass of a star.

Eddington has further criticized the work of Jeans in the realm of stellar equilibrium. Russell[18] has cleared away the mathematical conflict existing between the theories of these two investigators, showing that neither of their theories is accurate in the strictest sense of the word; the fact, however, that they agree so well with the observed data shows that they are good approximations.

[16] *Op. cit.*

[17] *M.N.* 85, 2, 1924.

[18] *M.N.* 85, 935, 1925.

CONCLUSION

While I have wandered from the main subject of the sun, to consider the source of stellar energy, the two topics are so intimately related that their solutions are identical. I consider that I have demonstrated the reasonableness of Jeans's theory by the manner in which it seems to fit the observed facts. There is, as I can see, no important objection to the hypothesis. It is too much to hope that the foregoing analysis is rigidly complete, but I confidently believe that the main points are established and that further modification will consist in the clearing up of details. The application of astrophysics and atomic theory to a new field appears to have met with considerable success. In spite of this success, however, caution is necessary. The present position of the theory advocated in this paper is somewhat analogous to the place once held by the theory of Helmholtz—*i.e.,* it is the only one sufficiently elastic to stretch over the region of known facts. Our knowledge is yet limited and, with our vision thus impaired, we can not predict the future. Some unforeseen event may upset our present hypothesis as completely as that of Helmholtz; we have built as securely as possible upon observation, and it remains for the future to test the accuracy of this or any other theory so established.

Philosophers may criticize the super-radioactive theory in that it fails to account for the presence of these atoms in the sun and stars. Until now, it seems to have been tacitly assumed that heavier elements were being evolved from lighter ones instead of the reverse process here pictured. This last question, however, is fortunately far enough outside the physical domain to be considered metaphysics. I prefer, then, with Jeans, not to attempt the answer. It is obvious that we must stop before we create something out of nothing.

SUMMARY

In an attempt to discover a reasonable explanation of the origin and duration of the solar radiation, all possible sources of energy are examined. The following hypotheses are reviewed and discarded, the arguments against their validity being too well known to necessitate a review at this place; (1) Original Heat; (2) Chemical; (3) Gravitational, (a) Meteoric, (b) Contraction; (4) Radioactive.

In view of the failure of the above hypotheses, serious consideration is given to the possible transmutation of matter into energy. Eddington's mass-luminosity relation appears to demand such a process as the general source of stellar radiation. It is shown that any theory which makes the production of energy a function of temperature and pressure is

subject to severe criticisms—(a) the observed rate of energy transformation is greater in the giant than in the hotter and denser dwarf stars; (b) the adiabatic nature of a star would be insufficient to regulate the generation of heat.

Jeans assumes that we have, in the center of stars, a quantity of atoms of atomic weight higher than uranium, whose super-radioactive powers lead to decomposition into energy. The success of the theory in accounting for the following observed facts is enough to demand its serious consideration.

1—Life of stars of order of 10^{13} years
2—Better value of the stellar absorption coefficient
3—Giant and dwarf stars
4—White dwarfs
5—Early spectral type of spectroscopic binaries
6—Relations between visual double stars
7—Sufficiently long time for evolution of orbits of visual binaries
8—Cepheid and Long Period Variables (?)

The main objection of Eddington to the theory appears to be invalid.

DONALD H. MENZEL

LICK OBSERVATORY,
Nov. 25, 1926.

EXUM PERCIVAL LEWIS

IN the death of Exum Percival Lewis on November 17, 1926, there was lost to science an inspiring teacher, a distinguished investigator in spectroscopy and astrophysics, a philosopher and an idealist. Professor Lewis was born in Washington County, North Carolina, on September 15, 1863. He was the son of Henry Exum Lewis, a noted physician, and Emma (Haughton) Lewis. Owing to the privations brought by the Civil War and to the death of his father when he was seven years old his elementary education was obtained entirely at home. As a boy he served as a printer's apprentice and as a young man accepted a position in the War Department at Washington, D. C. While thus employed he attended night classes at Columbian University (now George Washington University) from which he was graduated in 1888 with the degree of B.S. In 1890 he entered the Johns Hopkins University as a graduate student in physics, mathematics and astronomy, and from 1891 to 1895 he was an assistant in physics at that institution, having charge of the laboratory instruction. At the same time, from 1892 to 1895, first as instructor and then as assistant professor, he lectured evenings on general physics, electricity and heat, in the scientific school of Columbian University.

At Johns Hopkins University, under the inspiration of Professor Rowland, Professor Lewis began the work of an investigator in his chosen field of spectroscopy, receiving the degree of Ph.D. in 1895. His thesis, on the infra-red spectra of certain metals, represented practically the first accurate measurements of infra-red lines. His knowledge of astronomy and astrophysics, in addition to his attainments in physics, led, in 1895, to his being called to the University of California, where a physicist was needed who could give proper support to the astronomical work being undertaken on the campus at Berkeley in connection with the work at Lick Observatory. At the University of California he held the position of instructor in physics from 1895 to 1896; assistant professor from 1896 to 1902; associate professor from 1902 to 1908; professor from 1908 to the time of his death, serving after 1918 as the chairman of the department. From 1898 to 1900 he was on leave of absence on a Whiting Fellowship, engaged in spectroscopic research at the University of Berlin, making a systematic investigation of the effects produced by small quantities of other substances in the spectra of nitrogen, hydrogen and oxygen. In this work is found the first recognition of the fact, which has only recently been fully recognized, that the most profound changes in the character and appearance of the spectrum of a given element or substance can be produced by suitably modifying the excitation. It was in connection with this investigation that, in 1900, he discovered the afterglow in a vacuum tube containing nitrogen in which a slight trace of oxygen or water vapor was present. In 1904 he discovered the ability of this afterglow to excite the spectra of various solid substances introduced into the nitrogen-filled tube: this secondary excitation also persisting after the main discharge had ceased. These phenomena, extended by Lord Rayleigh and others, under the term "active nitrogen," have become of great importance. In addition to his researches in active nitrogen he investigated the band spectrum of nitrogen, especially the second positive group in the ultraviolet. His discovery of the effect that the introduction of self-induction in the circuit has on the band spectrum of nitrogen is still one of the most striking examples of what is now known to be the effect of changes in temperature upon any band. Among his other contributions to spectroscopy was the discovery of the continuous spectrum of hydrogen in the ultraviolet, with a determination of its limits and the condition most favorable to its production; the determination of several hundred new lines in the ultraviolet spectra of krypton and xenon; and the ultraviolet spectrum of the solar corona obtained with a quartz spectrograph of his own design. This spectrograph was made possible by a special grant from the Carnegie Institution.