Stellar Energy Sources

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1. INTRODUCTION

A LARGE part of this discussion will be concerned with thermonuclear reactions and how they affect the evolution of individual stars. These reactions affect the life history of a star very greatly, since they produce most of the energy which feeds the star's radiation. Were it not for the nuclear energy sources, the vast majority of stars we now see would be black dwarfs. I will only give a brief outline of the present state of the art, which difficulties have been overcome and which difficulties remain. I will not attempt to name the many authors who have contributed to advances in the field.[1]

For energy production in stars, only a small number of thermonuclear reactions is of importance and we do not need to know their reaction rates with great accuracy. However, nuclear reactions in stars are also of interest in another connection: According to one of two rival schools of thought, all elements in the universe other than hydrogen were not made at the "beginning of the universe," but were made from hydrogen in stars by means of nuclear reactions. For testing this hypothesis one needs to consider a very large number of nuclear reactions in great detail and needs to know the ratios of various reaction rates fairly accurately. Since many papers in the last few years have concentrated on the question of "element cooking," I will at least mention these considerations in passing.

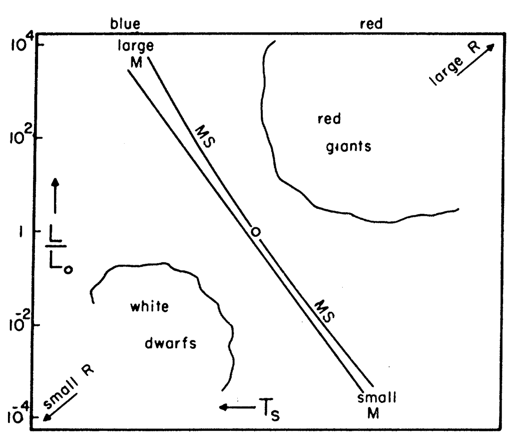

FIG. 1. Schematic Hertzsprung-Russell diagram for nearby stars of all ages. L is the luminosity, T_s is the surface temperature, M the mass and R the radius. *MS* stands for "main sequence." The circle denotes the position of the sun.

2. ASTROPHYSICAL OBSERVATIONS

The following is an oversimplified outline of some purely astrophysical observations relevant to stellar energy production and evolution: The most important are embodied in the Hertzsprung-Russell diagram, where one plots a star's absolute luminosity L (the total radiation emitted per second) against its effective surface temperature T_s, for a large number of stars.[2] Given L and T_s, the radius R of the star (or, more precisely, of its photosphere, the layer from which the observed radiation emanates) follows from the law of blackbody radiation. For a much smaller number of stars (too few, alas) the stellar mass M can also be obtained from observations.[3] The three quantities M, L, and R are the main link between stellar interior calculations and observation.

The main features of the Hertzsprung-Russell diagram—if stars of all ages, near and far, are included—are shown (highly schematic) in Fig. 1: First of all we have a fairly narrow band of points, the "main sequence" stretching from stars of low luminosity L and low surface temperature T_s to hot and luminous ones. To the right of the main sequence are the "red giants," stars of high luminosity and low surface temperature and hence with very large radii R. The red giants, unlike the main sequence, are scattered over a fairly large area of the Hertzsprung-Russell diagram. Finally, to the left of the main sequence, are the "white dwarfs," hot stars of low luminosity with very small radii.

We have fairly good statistics on the masses of main sequence stars (except the very luminous ones, which are rare): There is an almost one-to-one correspondence between the position of a star along the main sequence in an L–R diagram and its mass M, more luminous stars having larger masses (the luminosity increases very rapidly with increasing mass). White dwarfs are slightly less massive than the sun. Unfortunately we have very little reliable data on the masses of red giants, except that they are in general larger than the solar mass M_0. This paucity of quantitative data had led in prewar days to the "mass-luminosity relation," which is now thought to be partly incorrect: This relation supposed that any red giant had the same mass as a main sequence star

[1] The list of references is neither complete nor, necessarily, representative. The selection is biassed in favor of recent papers which include broader reviews of some topics or a large bibliography.

[2] (a) J. A. Hynek, *Astrophysics, A Symposium* (McGraw-Hill Book Company, Inc., New York, 1951), Chaps. 1 and 2 (b) Aller, *The Atmospheres of the Sun and Stars* (Ronald Press, New York, 1953); (c) R. D. Woolley and D. W. N. Stibbs, *The Outer Layers of A Star* (Clarendon Press, Oxford, 1953).

[3] See reference 2a, Chaps. 9 and 11; G. P. Kuiper, Astrophys. J. **88**, 472 (1938); P. Van De Kamp, Astron. J. **59**, 447 (1954); K. Strand and R. Hall, Astrophys. J. **120**, 322 (1954).

of the same luminosity. According to modern theories of stellar evolution, at least some red giants (those in globular clusters) are much more luminous than main sequence stars of the same mass (Sec. 9). Although "direct" measurements (i.e., analyses of binary systems) of red giant masses are still scanty, we now have at least indirect mass estimates supporting this hypothesis (from theoretical analyses of pulsating red giant stars[4] and from statistics[5] on the angular momentum of main sequence and red giant stars).

Another quantity of interest is the "chemical composition of the universe." We now have rather detailed information on the abundances of the various chemical elements and on isotope ratios in the atmospheres of many stars and in interstellar gas (spectroscopic analysis), as well as in meteorites and even (to some extent) in cosmic rays. Apart from some definite and interesting variations, there is a great similarity between the abundance ratios in such different components of our galaxy. This wealth of data on the "cosmic abundances" of the elements and isotopes[6] has stimulated development of theories on the origin of the elements. For the purpose of calculations on energy production and the interior structure of stars, a knowledge of the abundances of broad *groups* of elements is sufficient. The groups of most interest for this purpose are (together with their approximate *cosmic* abundances in percent, by mass): hydrogen (90%), helium (10%), carbon to neon (1%), and the metal group near iron (0.5%). Although this broad grouping of elements is sufficient, the results of stellar interior calculations are quite sensitive to variations of the chemical composition with radial distance in the interior of a star. Such variations cannot be observed directly and one must investigate the consequences of various assumptions regarding them.

3. STELLAR INTERIOR CALCULATIONS[7]

Calculations on the internal structure of a star in full equilibrium proceed as follows: For a star of a given mass M, *assume* some particular chemical composition as a function of radial distance throughout the star. We do *not* assume any law of energy production at the moment, but merely specify *where* the energy production occurs (whether it all comes from the center of the star or falls off with radial distance in a certain way, etc.). For main sequence stars at least, the energy production is largely concentrated in the central regions of the star and the results are not very sensitive to the exact extent of the energy producing region. The assumption that the star is spherically symmetric and in a steady state leads to two equilibrium equations, one relating the pressure gradient to the gravitational force, the other relating the temperature gradient to the radially outgoing energy flux. These two equations permit a single infinity of solutions for $\rho(r)$, $T(r)$ and $L(r)$—the density, temperature, and energy flux as a function of radial distance r. The single infinity of solutions is connected with the fact that we have not yet specified the law of energy production. If we specify one further quantity, say the central temperature T_c, the solution then gives $\rho(r)$, $T(r)$ and $L(r)$ uniquely and hence also the luminosity $L=L(\infty)$, i.e. the total amount of energy radiated per second. In the more approximate kinds of calculations, ρ and T become zero for a finite value of r and we identify this value with the stellar radius R.

Consider now the case where the rate of energy production (nuclear or otherwise) is known as a function of temperature, density and chemical composition. Since the rate of energy production, integrated over the whole star, must equal the total luminosity L, we can now pick out the one correct solution (i.e., the correct central temperature T_c) out of the singly infinite set (if we have guessed reasonably correctly, in our original assumption, where the bulk of the energy production occurs). In our single infinity of solutions, the luminosity L is fairly insensitive to the value of T_c, but depends quite strongly on the mass and over-all chemical composition of the star. To put it more crudely, the luminosity L is largely determined by the atomic physics and kinetic and gravitation theory which enters the equilibrium equations; the nuclear physics which gives the rate of energy production (which is very temperature sensitive) merely determines the central temperature at which the energy production keeps pace with the luminosity.

4. MAIN SEQUENCE STARS

The simplest assumption about the spatial distribution of chemical composition and energy production (the "stellar model") is the following: We assume *uniform* chemical composition throughout the star and that the energy production is concentrated towards the center of the star. We now have overwhelming evidence to suggest that this kind of stellar model gives a good representation of a main sequence star (at least a fairly young one): We suppose the star was formed from a gas of uniform chemical composition, consisting mainly of hydrogen. The star is in a steady state since its central temperature is just high enough for the slow conversion of hydrogen into helium to produce enough energy to supply the radiation (carbon cycle and proton chain, Sec. 7). The energy production is concentrated towards the center, since the thermonuclear reaction rates are very temperature sensitive and the temperature decreases from the center outwards. Finally, *if*

[4] A. R. Sandage, Astrophys. J. **123**, 278 (1956); V. C. Reddish, Monthly Notices Roy Astron. Soc. **115**, 32 (1955).
[5] A. R. Sandage, Astrophys. J. **122**, 263 (1955).
[6] H. S. Brown, Revs. Modern Phys. **21**, 625 (1949); H. E. Suess and H. C. Urey, Revs. Modern Phys. **28**, 53 (1956).
[7] B. Strömgren, Ergeb. exakt. Natur. **16**, 465 (1937); S. Chandrasekhar, *An Introduction to the Study of Stellar Structure* (University of Chicago Press, Chicago, 1939); S. Chandrasekhar, *Astrophysics, A Topical Symposium* (McGraw-Hill Book Company, Inc., New York, 1951), Chap. 14; L. H. Aller, *Nuclear Transformations, Stellar Interiors, and Nebulae* (Ronald Press, New York, 1954).

the star is fairly young, the total amount of hydrogen which has been converted into helium in the central regions of the star is small and the chemical composition is still almost uniform.

Mention should be made of some of the sources of inaccuracies in stellar interior calculations:

(i) The rates of nuclear energy production are discussed in Sec. 7. These rates are now known not with very good, but with adequate, accuracy.

(ii) We also need to know the coefficients occurring in one of the two equilibrium relations, the energy transport equation. Throughout most of a star, the energy transport is carried by radiation and the coefficient we need is the opacity. Atomic theory is well enough understood that, in principle, one can calculate the opacity coefficient as a function of temperature, density and chemical composition. In practice such calculations are very tedious but, with the help of computing machines, reliable tables[8] of opacity coefficients have by now been computed.

(iii) On the other hand, we do not yet have sufficiently quantitative theories of turbulence and convection. In the deep interior of some main sequence stars (the hotter ones, which burn hydrogen on the carbon cycle) the energy transport is carried by convection, but in these regions convection is a very efficient process and the calculations are not seriously affected by our poor estimates of convection rates. However, in stars with a low enough surface temperature that the hydrogen in the photosphere is not yet fully ionized, we also have another convection zone just below the photosphere. The fractional mass of the star contained in this outer convection zone is quite small (less than one percent for our sun) and this zone has a negligible effect on the star's interior or on its luminosity. However, we have to contend with the observational definition of the star's "radius" R which, from the theoretical point of view, is rather unfortunate: One observes the radius of the photosphere (about one optical thickness only between it and the outside). which is an extremely tenuous envelope of the star containing only a minute fraction of its mass. The radius of this photosphere is unfortunately quite sensitive to the details of the outer convection zone (and to inaccuracies in the calculation), whereas the root mean square radius for the star's mass, for instance, would be quite insensitive. Nevertheless, quite satisfactory results have been obtained[9] even for main sequence stars cooler than the sun ("red dwarfs"), for which the outer convective zone is particularly important: One assumes a chemical composition of the star (of given mass) equal to that of the star's amosphere One then *adjusts* a parameter, connected with the depth of the hydrogen convection zone, so that the calculated radius agrees with the observed one. The necessary value of this parameter is found to lie within the limits given by the present incomplete theories of convection. One can then calculate the star's luminosity, which is found to be in reasonable agreement with the observed luminosity.

(iv) For main sequence stars of unknown age we have an added uncertainty. In the absence of mixing, whatever helium has been transformed out of hydrogen in the star's past history has accumulated in its deep interior (where the conversion mainly went on) and it now has a slightly nonuniform chemical composition.[10] Calculations for the sun,[11] which neglect the outer convective zone and the chemical inhomogeneity in its interior, have led to discrepancies with observation. However, since the sun's age is known to be 4 or 5 billion years, one can calculate the excess amount of helium in its interior. Calculations,[12] which take account of this chemical inhomogeneity and treat the outer convection zone as described previously, give a luminosity in agreement with the observed one. According to these calculations, the sun is about 30% more luminous now than when it was still young and of homogeneous composition. In fact, the finite width of the main sequence band on a Hertzsprung-Russell diagram for nearby stars of all ages is now thought to be due mainly to the variations in age (and hence in the degree of chemical inhomogeneities): The observed main sequence for a single galactic cluster, consisting of young stars of the same age, is much narrower[13] and one can extrapolate to a well defined "zero-age main sequence" from these observations.

5. EVOLUTIONARY SCHEME

From the equilibrium equations for a steady-state star one can derive a very simple relation somewhat resembling a virial theorem which relates the gravitational to the thermal energy content of the star: For any particular model one can calculate the gravitational potential energy V_{gr} of the star which is of the order of magnitude of $-GM^2/\bar{R}$, where M is the mass and $\bar{R}$ the (root-mean-square) radius of the star. The thermal energy content E_{th} is $Nk\bar{T}$ where N is the total number of ions and $\bar{T}$ is the average temperature which for many models is a factor of 5 or 10 smaller than the central temperature. Our simple relation states that the ratio of $-V_{gr}$ to E_{th} is of the order of and slightly *larger* than unity for most stellar models. Thus in

[8] G. Keller and R. E. Meyerott, Argonne National Laboratory Repts. Nos. 4771 and 4856 (1952) and an unpublished paper; H. Zirin, Astrophys. J. **119**, 371 (1954); I. Epstein and L. Motz, Astrophys. J. **120**, 156 (1954).

[9] D. E. Osterbrock, Astrophys. J. **118**, 529 (1953).

[10] This is particularly serious for stars more luminous than the sun, which burn hydrogen rather quickly. For Sirius A, for instance, see T. L. Swihart, Astrophys. J. **118**, 577 (1953).

[11] I. Epstein and L. Motz, Astrophys. J. **117**, 311 (1953); P. Naur, Astrophys. J. **119**, 365 (1954); G. O. Abell, Astrophys. J. **121**, 430 (1955).

[12] Schwarzschild, Howard, and Härm, Astrophys. J. (to be published).

[13] H. L. Johnson and C. F. Knuckles, Astrophys. J. **122**, 209 (1955); H. L. Johnson and W. A. Hiltner, Astrophys. J. **123**, 267 (1956); Johnson, Sandage, and Wahlquist, Astrophys. J. **124**, 81 (1956).

going from an equilibrium state of one radius to another state of smaller radius the star liberates excess energy[14] which can act as a source for the energy that is radiated away. As a general rule then, when a star has no nuclear energy sources operating in its interior at any stage, the main part of its mass will undergo gravitational contraction. According to our "virial theorem," the mean temperature of the star will also increase during the contraction, in addition to the energy release which feeds the star's luminosity.

Crudely speaking, we can divide the life history of an individual star (according to present-day theories) into three stages: (i) In the first stage the star starts off as a fairly dilute and cold gas mass. Its central temperature is much too low for any thermonuclear reactions to take place. The star is therefore not in a truly steady state, but it will undergo slow gravitational contraction and its luminosity is supplied by the release of excess gravitational energy during the contraction (see Sec. 6). At the same time the temperature in its interior increases towards the values at which nuclear energy production is appreciable. (ii) In the second stage the interior temperatures are just right for the H−He conversion to supply all the energy which goes into the star's luminosity. At this stage the star is on the main sequence, already discussed in Sec. 4, and remains in this steady state for a long time. (iii) After the star has stayed on the main sequence long enough for an appreciable part of its interior to have exhausted its hydrogen content, the star begins to move off the main sequence again. The details of the subsequent evolution are complicated and depend strongly on the star's mass (and possibly on other factors, such as angular momentum). However, at the early phases of this evolution, each star seems to move off the main sequence in the direction of the red giant region, i.e., its luminosity increases and surface temperature decreases. It is now believed that the inner core of the star contracts gravitationally during this early phase, but the radius of its photosphere increases (Sec. 4). At later phases of the evolution, high enough central temperatures may be reached for further nuclear reactions to take place (Secs. 8 and 9).

The comparison of theories on stellar evolution with observational data is helped greatly by two facts: On the observational side we are helped by the existence of various groups of stars for which we have good reason to believe that all the stars inside one group are, at least roughly, of the same age. There are various kinds of such groups: The "globular clusters" each contain a very large number (of the order of 10^5) of stars. These clusters are members of "stellar[15] population II", i.e., stars formed in the early stages of the life of our galaxy as a whole. On the other end of the scale we have the "expanding star associations," containing only a small number (about 100) of stars. Such an association seems to be a dynamic structure and the stars in it were probably formed at the same time. The actual age varies from one association to another, but they are all very young (down to about 10^6 years) and are extreme examples of "stellar population I," Intermediate between these two types of star groups, both regarding age and number of stars, are the "galactic clusters" (or "open clusters").

[14] There are some exceptions to this rule, notably stars of mass less than a certain limit and high enough density that the electrons are degenerate but have nonrelativistic energies. In this case one can get a stable configuration in which no excess energy is liberated either by contracting or expanding the star's radius. White dwarf stars are thought to be in (or near) such configurations.

TABLE I. The time scales t(i), t(ii) and t(iii) for the three evolutionary stages for stars of two different masses M and luminosities L(M_0 and L_0 refer to the sun; the times t are in years).

M	L	t(i)	t(ii)	t(iii)
M_0	L_0	20×10^6	15×10^9	?
$1.3M_0$	$5L_0$	7×10^6	3×10^9	10^8

On the theoretical side we are helped by the fact that an individual star spends a very much longer time "sitting still" on the main sequence (stage ii) than it takes to contract towards the main sequence (stage i) or to evolve away from it (stage iii). The difference between the time-scales of stages (i) and (ii) comes about as follows: The mean thermal energy per ion, $k\bar{T}$, for a main sequence star is less than one kev ($\bar{T}<10^7$°K) and the gravitational energy release per ion during the *whole* gravitational contraction to the main sequence is of the same order of magnitude. On the other hand, the overall energy release in the nuclear H−He conversion is 6.5 Mev per H atom, orders of magnitude more than the gravitational energy content. The time scale of stage (iii) is short partly because the over-all energy release is smaller than in stage (ii) and partly because the luminosity is much larger during stage (iii). Rough figures for the time-scales t(in years) for the three stages are given in Table I for a star of solar mass M_0 and a slightly more massive one.

6. EARLY GRAVITATIONAL CONTRACTION

Let me describe in slightly more detail the first evolutionary stage, during which the star is too cool to burn hydrogen. I will not discuss at all the original "birth of the star," i.e., the processes that lead from an irregular cloud of cold and dilute gas and dust to a spherical mass of gas which (while much cooler than a main sequence star) is hot enough to be optically opaque. These early processes are very complicated, depend strongly on the distribution of dust and turbulence, and we understand the birth process poorly, if at

[15] W. Baade, "Symposium on astrophysics," University of Michigan (July 1953, unpublished report); W. Baade, Scientific Am. **195**, 92 (1956); A. R. Sandage, Mem. soc. roy. sci. Liége **14**, 254 (1954).

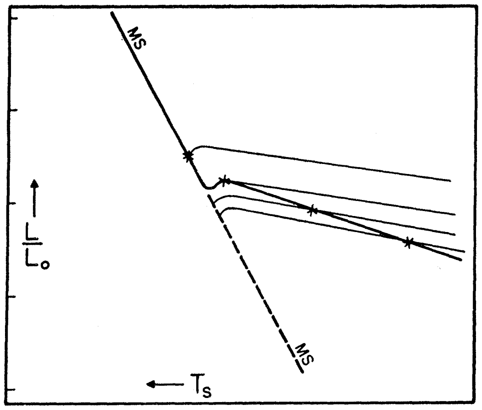

FIG. 2. Schematic Hertzsprung-Russell diagram for a group of young stars of the same age. The heavy solid line is the observed diagram, the dotted heavy line is the missing portion of the main sequence. The light lines are the evolutionary tracks of individual stars, the crosses denote the positions they have reached at the present time.

all. Let us start with a spherical star of low density and central temperature of the order of 10^5°K, so the hydrogen in its interior is hot enough to be ionized but too cold to undergo thermonuclear reactions.

The evolution of such a star can be treated very crudely by means of the "quasi-steady-state approximation": We disregard the question of energy production at the moment, assume a *steady*-state star with uniform chemical composition and find the temperature, density and energy flux throughout the star, as given by the equilibrium equations, for a given initial value of the central temperature T_c. From such a calculation we also obtain the luminosity L and the thermal and gravitational energies E_{th} and V_{gr}. One then repeats this calculation for a series of (successively larger) values of T_c. We then pretend that the contraction and heating up of the actual star is represented by the "movement" along this series of steady-state solutions. The time-scale of this "movement" is obtained by balancing the release of excess gravitational energy against the energy radiated away,

$$\frac{d}{dT_c}[V_{\text{gr}}(T_c)+E_{\text{th}}(T_c)]\times\frac{dT_c}{dt}=-L(T_c). \qquad (1)$$

We have thus obtained the luminosity and radius of the star as a function of time.[16]

As mentioned before, comparison of evolutionary calculations with observation is helped (i) by the existence of groups of stars of the same age and (ii) by the fact that an individual star spends a much shorter time in its stage of gravitational contraction than it does on the main sequence: The heavy solid curve in Fig. 2 shows (schematcially) the observed Hertzsprung-Russell diagram for a very young star-group[17] (about 10^6 years old). The upper part of the main sequence is present, but the lower part (dotted line, low luminosity stars) is missing. In its place we have low luminosity stars of very large radius (small surface temperature). The light lines represent the evolutionary track of individual stars, the cross on each line represents the stage to which each star has evolved during the common lifetime of the group. The more luminous (more massive) stars evolve more rapidly, have already reached the main sequence and "stay put" on it (at least for times much longer than the age of the group). For the less luminous (and less massive) stars we see a "snapshot picture" of various stages during the gravitational contraction—the earliest stages for the least luminous stars which evolve most slowly. The heavy line ("contraction branch") to the right of the main sequence, the observed "snapshot," does not differ very much from the evolutionary track of an individual star. In other words, stars on different parts of the "contraction branch" have similar masses and will lie close to each other by the time they have all reached the main sequence (stars of *much* smaller mass simply haven't contracted enough to radiate sufficiently in the visible spectral region).

The "quasi-steady-state-approximation" is reasonably good in the present case: The luminosity of a star is given mainly by the equilibrium equations, not by the law of energy production, and is not very different if the energy source is gravitational rather than nuclear. Dynamic effects have been neglected. That is, we have neglected the imbalance between gravitational force and pressure gradient, which produces the inward motion of matter during the contraction. This imbalance is very small and the kinetic energy contained in the contraction itself is very small compared with the thermal or gravitational energy contant. To get a feeling for the orders of magnitude—if there were no pressure gradient at all, the star would collapse in a matter of hours compared with the actual contraction times of the order of 10^6 years. Nevertheless, the quasi-steady approximation is only in semiquantitative agreement with more accurate calculations[18] on the detailed evolution of a star. For instance, the "dip" near the main sequence on the heavy line in Fig. 2, which is found both observationally and in the accurate calculations, would not be obtained from a crude quasi-steady-state calculation.

One minor point bears mentioning: If a star had originally contained large amounts of deuterium, lithium, beryllium, or boron, these substances would have largely "burned up" during the gravitational contraction before reaching the main sequence (see Sec. 7). The Hertzsprung-Russell "snapshot picture" for such a group of stars would then have deviated from that shown in Fig. 2. The absence of clear-cut effects of this nature in the observations to date thus puts an

[16] E. E. Salpeter, Mem. soc. roy. sci. Liége 14, 116 (1954).
[17] M. F. Walker, Astron. J. 59, 333 (1954).
[18] Henye, LeLevier, and Levée, Publ. Astron. Soc. Pacific 67, 154 (1955).

upper limit on the original abundances of these elements. However, these upper limits at present are in any case larger than the various estimates from other considerations for these abundances.

7. THERMONUCLEAR REACTIONS WITH HYDROGEN

From the point of view of stellar energy production, by far the most important thermonuclear reactions are two series of reactions called the proton-proton chain (*p-p*) and carbon-nitrogen (C−N) cycle. The net result of each of these series of reactions is

$$4H^1 \rightarrow He^4 + 2\nu + 26.7 \text{ Mev}. \tag{2}$$

Of this energy release, only about 0.5 Mev (*p-p*) or 1.4 Mev (C−N) are lost in the form of neutrino (ν) kinetic energy, the rest is transformed into thermal energy inside the star. The overwhelming importance as stellar energy sources of these two reaction chains is due the fact that hydrogen constitutes the bulk of stellar matter and that the energy release, per unit mass, is greater in the H−He conversion than for any other nuclear processes in stars. The rate of energy production per g/sec from these two chains is plotted roughly against temperature in Fig. 3. The carbon cycle rate increases much more steeply with temperature and dominates for the more luminous and massive stars. The *p-p* chain dominates slightly for the sun and strongly for all less massive (and less luminous) main sequence stars.

Because of their importance, the proton-chain and carbon cycle have been restudied and reviewed[19] extensively in the last few years so I shall not describe them any further. Instead, I will give some general remarks about the systematics of thermonuclear reactions in stars in general, in particular about those[20] which involve hydrogen as one of the reactants.

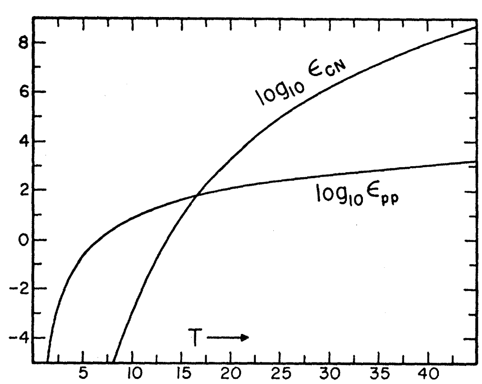

FIG. 3. The energy production on the proton-proton chain (ϵ_{pp}) and on the carbon-nitrogen cycle (ϵ_{CN}), plotted against temperature T (in units of 10^6°K). The curves are for $\rho x_H^2 = 100$ and $x_{CN}/x_H = 0.005$, where ρ is density in g/cc and x_H, x_{CN} are the abundances (by mass) of hydrogen and of the C, N group.

The time scale of these thermonuclear reactions is enormously long, not only compared to nuclear times, but even long compared to reaction times in somewhat related terrestrial devices. The reason for this is essentially the following. The luminosity of the star is essentially given, not by nuclear physics, but just by the opacity and hydrodynamics of the star. Thus, it is really the atomic physics that calls for a particular luminosity, and therefore a particular rate of energy production. That rate is quite small and the total energy content in nuclear reactions is quite large. From these two considerations it follows that the time factor of these thermonuclear reactions in stars has to be of the order of a million to billions of years.

The temperature has to adjust itself in such a way as to give these very long time scales. That is, the temperature must be such that the thermal energy per ion will be extremely small compared to the Coulomb barrier (we will only be talking about reactions between charged particles for the moment). When the ratio between the Coulomb barrier and the thermal energy is of the order of a thousand, the rates are obviously extremely small. One of the consequences of this is that most of the energy production comes from a very narrow energy range, large compared to the thermal energy, small compared to the barrier height, where the product of the Maxwell-Boltzmann factor and the Coulomb barrier penetration factor (both small) has a maximum. For people trying to calculate reaction rates in the stars, this has a rather unfortunate consequence. Since this energy range is rather narrow and also lies at such a low energy, the cross sections cannot be measured directly in the laboratory. Also, they are very sensitive to resonances in the reactions which may occur in or near this narrow energy region and which are very difficult to observe. But at least that keeps both the theorists and experimentalists busy.

You can see then that the rate of these reactions is very temperature-sensitive, and also depends very strongly on the charge of the particles involved. Another thing that follows is that we need only talk of exothermic nuclear reactions, as the endothermic ones are almost impossible when you only have a few kilovolts of kinetic energy. Furthermore, since the time scale is so long, these reactions occur only with stable nuclei; in other words, if a beta-active nucleus is made in one reaction, it will have plenty of time to beta decay before it will absorb another proton or alpha particle.

As to the important reactions where protons are absorbed by various other kinds of nuclei, there are essentially two main trends which determine what is happening. One of them is just that, in the packing

[19] E. E. Salpeter, Phys. Rev. **88**, 547 (1952); E. A. Frieman and L. Motz, Phys. Rev. **89**, 648 (1953); W. A. Fowler, Mem. soc. roy. sci. Liége **14**, 88 (1954); Bosman-Crespin, Fowler, and Humblet, Bull. soc. roy. sci. Liége, Nos. 9–10, 327 (1954).

[20] E. E. Salpeter, Phys. Rev. **97**, 1237 (1955); Fowler, Burbidge, and Burbidge, Astrophys. J. **122**, 271 (1955). The proton-proton reaction does not fit into this scheme, since it involves a beta decay.

fraction curve, the binding energy per nucleon increases up to iron, which implies that in general (p,γ) reactions are exothermic. But that is not the whole story. The main part, or at least the other part, is the fact that alpha particles and also $(N=Z=2n)$ nuclei are particularly stable.[21] For this reason, on $(N=2n+2, Z=2n+1)$ nuclei, (p,α) as well as (p,γ) reactions will in general be exothermic. Even though the (p,γ) reaction would release more energy, a reaction resulting in the emission of a particle has a larger partial width than a radiative transition. This has the result that a (p,α) reaction will usually win out, providing the energy of the alpha particle is not so small that the barrier penetration factor prevents it. This has the important consequence that, given hydrogen and some fairly light nucleus, one does not just get successive building on by (p,γ) reactions and beta decay in one long chain up to the iron group. Rather, one gets cycles of reactions, of which the carbon-nitrogen cycle is by far the most important, but nevertheless only one, example.

The net result in each of these cycles is that of Eq. (2). i.e., the conversion of hydrogen into helium, with the other nuclei acting merely as catalysts: Starting from the $(Z=N=2n)$ nucleus three (p,γ) reactions and two positron-emitting beta decays (occurring in different orders in the different cycles) lead to the $(N=2n+2, Z=2n+1)$ nucleus. The (p,α) reaction on this nucleus then completes the cycle. The competing (p,γ) reaction, if it were important, would convert the original nuclei into the $(Z=N=2n+2)$-nucleus instead of reproducing the lighter nuclei. We give below four examples of such cycles, the four beta-stable nuclei that occur in each and the energy releases of the competing (p,α) and (p,γ) reactions.

(iii) C^{12}, C^{13}, N^{14}, N^{15}; $(p,\alpha)C^{12}+5.0$ Mev; $(p,\gamma)O^{16}+12.2$ Mev.

(v) Ne^{20}, Ne^{21}, Ne^{22}, Na^{23}; $(p,\alpha)Ne^{20}+2.4$ Mev; $(p,\gamma)Mg^{24}+11.5$ Mev.

(vi) Mg^{24} Mg^{25}, Mg^{26}, Al^{27}; $(p,\alpha)Mg^{24}+1.6$ Mev; $(p,\gamma)Si^{28}+11.6$ Mev. (3)

(vii) Si^{28}, Si^{29}, Si^{30}, P^{31}; $(p,\alpha)Si^{28}+1.9$ Mev; $(p,\gamma)S^{32}+4.6$ Mev.

In both the C−N and Ne−Na cycles, the (p,α) reaction does in fact dominate over the (p,γ) reaction and these nuclei are not lost during their cycles. The branching ratios of the two competing reactions, both in the Mg−Al and the Si−P cycle, depend on the position of resonance levels, which are not yet known, but it is quite likely that the Coulomb barrier for the alpha particle will depress the (p,α) rate below the (p,γ) rate.

In reality, the exceptions to our "cycle rule" are as important as are the good examples: In particular, the cycles with $n=1$, 2, and 4 are missing. For $n=1$, there is no $He^4(p,\gamma)$ reaction and both lithium isotopes are broken down to helium without being replenished. For $n=2$, we "almost" have a Be−B cycle, but the Be^8 formed in the last reaction is unstable and breaks up into two alpha particles. Thus the beryllium and boron isotopes are also broken down into helium without being replenished. Finally, for $n=4$, there is no O−F cycle because (p,α) reactions on O^{17} and O^{18} (as well as on F^{19}) are possible. If the full chain of reactions is uninterrupted, the oxygen and fluorine isotopes are thus converted into isotopes of the carbon-nitrogen group.

To return to the relevance of these proton reactions to stellar interiors: The thermonuclear rates of the various reactions decrease strongly with increasing nuclear charge and increase strongly with temperature. The proton reactions on the Li, Be, and B isotopes are sufficiently fast already at temperatures much smaller than the central temperatures of main sequence stars. Since these nuclei are converted into helium, rather than recycled, they are burned up during the early contraction of a star. In a main sequence star, the bulk of the hydrogen takes part in the C−N cycle (or p-p chain). At these temperatures, characteristic for the C−N cycle, the Ne−Na cycle and the $O^{16}(p,\gamma)$ reaction proceed rather slowly. These reactions are unimportant as energy sources but, at least in the hottest stars which still contain an appreciable amount of hydrogen, may be of importance regarding theories of element formation. In particular, these reactions may provide a source of O^{17} and Ne^{21} which, in turn, can undergo reactions which produce neutrons.

8. THERMONUCLEAR REACTIONS WITHOUT HYDROGEN

As outlined in Sec. 5, stars which have exhausted a large fraction of their hydrogen will leave the main sequence; their interior contracts and heats up. Before discussing the evolution of such stars, I will outline what types of thermonuclear reactions can go on in a large gas mass, largely devoid of hydrogen, as its temperature is raised very slowly.

We consider a gas of almost pure ionized He^4, possibly with small amounts of O^{16}, the isotopes of the C−N and Ne−Na groups and of the metals present. At temperatures of a few times 10^7°K, no nuclear reactions proceed at any appreciable rate: The Coulomb barrier is too large for any reaction other than the collision of two alpha particles, but such a collision cannot lead to any exothermic reaction (Be^8 is unstable). The only exothermic reaction which can occur in pure helium is the conversion of three alpha particles into one carbon nucleus,[22]

$$3\,He^4 \rightarrow C^{12}+\gamma+7.66 \text{ Mev.} \tag{4}$$

[21] N and Z are the number of neutrons and protons in the nucleus, n is an integer. We are considering fairly light nuclei at the moment.

[22] E. J. Öpik, Proc. Roy. Irish Acad. **A54**, 49 (1951); E. E. Salpeter, Astrophys. J. **115**, 326 (1952).

The reaction rate for such a "triple collision" might be expected to be extremely slow at densities of 10^3 to 10^5 g/cc, unless the temperature is very high indeed. In fact, the speed of the reaction in Eq. (4) is increased enormously by the chance coincidence of two resonance levels in two nuclei occurring in the most opportune energy regions: Although Be^8 is not stable, its ground-state energy is not much higher than that of two alpha particles with thermal kinetic energies (for temperatures of about 10^8°K). We thus have a dynamic equilibrium set up in which a certain small fraction of the matter is in the form of Be^8. The other resonance of interest[23] is the second excited state in C^{12}, which lies at an energy slightly larger than that of a Be^8 nucleus plus an alpha particle plus thermal kinetic energy. The He$-$C conversion thus takes place by way of an (α,γ) reaction on Be^8 through the second excited level of C^{12}.

Much experimental and theoretical work has been done on this resonance level in C^{12}, the most critical part of the key reaction to all later reactions. The rates of this reaction, at various temperatures and densities, are known to within about a factor of ten either way[24]: The energy of the C^{12} level has been measured very accurately and it has been verified that it has the right spin and parity to be formed from Be^8 plus an alpha particle. The same experiments have given an upper limit for the partial width of transitions to the ground state from this level. Inelastic electron scattering experiments at Stanford give, indirectly, a lower limit for this width and theoretical estimates for its actual value have also been made.

The $3\alpha \rightarrow C^{12}$ reaction time is of the right order of magnitude (10^6 to 10^7 years) for stellar energy production at temperatures of about 1×10^8°K (for densities of the order of 10^4 g/cc). At these temperatures, further (α,γ) reactions also go on, starting with the C^{12} which has been formed. A chain of such (α,γ) reactions could, in principle, build up $(N=Z=2n)$ nuclei up to Ca^{40}. At temperatures of about 1×10^8°K, however, only the reactions

$$C^{12}(\alpha,\gamma)O^{16}+7.2 \text{ Mev}; \quad O^{16}(\alpha,\gamma)Ne^{20}+4.8 \text{ Mev} \quad (5)$$

proceed rapidly enough. The net effect of these reactions is then the depletion of He^4, the buildup of C^{12}, O^{16}, and Ne^{20} (and, possibly, a little Mg^{24}), accompanied by an energy release of about 0.9 Mev per nucleon (compared with about 6.5 Mev per nucleon in the H$\rightarrow$He conversion). The reaction rates are known accurately enough for the purpose of stellar energy production, but are not yet accurate enough from the point of view of element-synthesis: In the $O^{16}(\alpha,\gamma)$ reaction, in particular, the possible effects of two resonance levels in the right energy region are still unknown. We therefore do not know yet the abundance ratio of O^{16} to Ne^{20}, which will be produced by this chain of reactions.

Another type of reaction is of importance for element synthesis at these (or even slightly lower) temperatures. Again because of the great stability of light $(Z=N=2n)$ nuclei, (α,n) reactions on some $(Z=2n, N=2n+1)$ nuclei are exothermic. In particular, (α,n) reactions on the nuclei C^{13}, O^{17}, and Ne^{21} proceed rapidly enough[25] at these temperatures. These isotopes are much too rare for reactions involving them to serve as a significant energy source. On the other hand, even fairly small amounts of neutrons may be of importance in synthesizing many of the less abundant isotopes. In addition, the nuclei C^{13}, O^{17}, and Ne^{21} may be replenished to some extent (Sec. 7) if small amounts of hydrogen are introduced into the gas mass (e.g., by mixing in from the outer layers of the star which are still hydrogen-rich).

Calculations have also been made[26] on reactions that might take place at still higher temperatures in a gas which is helium-deficient, as well as containing no hydrogen, i.e., consists mainly of C^{12}, O^{16}, and Ne^{20}. At temperatures of about 1×10^9°K two different types of reactions become important. The one type involves the collision between two of the more abundant nuclei. The reaction proceeding at the lowest temperature (from about 0.5×10^9°K up) involves the collision of two C^{12} nuclei, resulting in one of the following three possibilities

$$Mg^{24}+\gamma+14 \text{ Mev}, \quad Ne^{20}+\alpha+5 \text{ Mev}, \quad Na^{23}+p+3 \text{ Mev}. \quad (6)$$

The other types of reaction involve first of all endothermic (γ,α) reactions. These are initiated by photons with energies "way up in the tail" of the blackbody radiation spectrum. These photodisintegrations are rare, even at these high temperatures, but are followed immediately by the inverse processes, (α,γ) captures, on various nuclei. The net result of all these reactions is a tendency for the lighter and less stable nuclei to be destroyed and the slightly heavier and more stable nuclei, up to about silicon or sulfur ($A\sim30$), to be built up. At slightly higher temperatures still, about (2 to 3)$\times10^9$°K, a whole host of reactions begins to take place. Besides the types of reactions already mentioned, (γ,p) and (p,γ) reactions followed by beta decays are also possible, which can result in nuclei containing more neutrons than protons. The end result of all these reactions, at about 3×10^9°K, is a tendency toward statistical equilibrium of the relative abundances of the nuclides according to their binding energy per nucleon; i.e., a peak is built up in the region of the most stable nuclei, in the neighborhood of Fe^{56}.

[23] Dunbar, Pixley, Wengel, and Whaling Phys. Rev. **92**, 649 (1953).

[24] (a) E. E. Salpeter in "Symposium on astrophysics," University of Michigan (July 1953, unpublished report); (b) F. Hoyle, Astrophys. J. Suppl. Ser. **1**, 121 (1954); (c) Hayakawa, Hayashi, Imoto, and Kikuchi, Progr. Theoret. Phys. (to be published); (d) W. A. Fowler *et al.* Phys. Rev. (to be published).

[25] A. G. Cameron, Astrophys. J. **121**, 144 (1955); Fowler, Burbidge, and Burbidge, Astrophys. J. **122**, 271 (1955).

[26] See references 24(a) and (b). S. Nakamura (unpublished work).

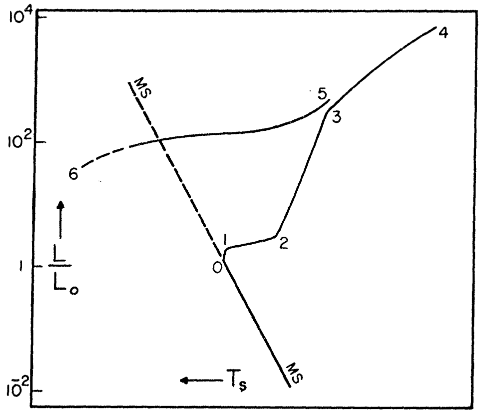

Fig. 4. Schematic Hertzsprung-Russell diagram for a typical globular cluster. The dotted line represents the missing portion of the main sequence.

The energy release per mass in all these later reactions is quite small: The whole chain of reactions leading from O^{16} to Fe^{56}, say, only produce a total energy release of about 0.6 Mev per nucleon. To summarize, we have found possible nuclear energy sources at three different temperature ranges: (i) The H→He conversion at (1 to 3)$\times 10^{7}$°K with a large release of energy. (ii) The He→C, O, Ne conversion at (1 to 2)$\times 10^{8}$°K with a smaller energy release. (iii) A host of reactions converting the last group into the iron-group at (0.5 to 3)$\times 10^{9}$°K with a very small energy release.

9. EVOLUTION OF POPULATION II RED GIANTS

Let us return now to stage (iii), outlined in Sec. 5, in the evolution of an individual star, its history after it leaves the main sequence. We now have a large amount of observational data on the Hertzsprung-Russell diagram for stars[27] in globular clusters (extreme cases of stellar population II). The various globular clusters (seven of them have been analyzed in detail so far) are thought to be of about the same age (5 to 6×10^{9} years) and have remarkably similar Hertzsprung-Russell diagrams, shown schematically in Fig. 4.

As Fig. 4 shows, the upper part of the main sequence is missing, the break (point 0) occurring at stars of about twice the sun's luminosity (mass about 1.1 M_0). Instead, we have the curve "to the right and up" of the main sequence, with fairly definite changes of slope at the points marked 1 to 6. According to calculations described below, the evolution of an individual star off the main sequence is very rapid (especially after point 2). The "snapshot picture" in Fig. 4 lies then fairly close to the evolutionary track traced out by an individual star and the masses of the various stars along various parts of the snapshot vary very little (from about $1.1M_0$ at point 1 to about 1.2_5M_0 at point 6).

Much theoretical work has been done in recent years on the internal structure of such stars. The latest calculations[28] are in remarkably good semiquantitative agreement with the observational data. I shall only outline the physical features implied by the theoretical results: Until the star has converted about 10 to 15% of its hydrogen mass into helium (point 1) it does not move far off the main sequence (our sun has progressed about halfway towards point 1). But, by this stage, it has developed a marked inhomogeneity: We have a central core, consisting mainly of inert helium at a uniform temperature, surrounded by a hydrogen-rich spherical shell in which the H−He energy production now takes place. As more hydrogen "burns out," the fraction q of the star's mass inside the helium core grows and the structure of the star varies quite markedly with q:

As the core mass q increases, the density of the core increases, the outer envelope of the star becomes more tenuous (radius increases) and the luminosity increases. The time scale of this evolution is determined by the rate at which hydrogen must be burned up (adding its mass to q) in order to supply the luminosity. Between point 1 and about point 3, this rate is small enough so that the rate of release of gravitational energy during the contraction of the core is small. The core is then almost isothermal, does not heat up much while its density increases (the temperature of the hydrogen-burning shell is kept near 3×10^{7}°K by the carbon cycle) and the electrons in the core's interior are degenerate. Near point 3, however,[29] the rate of the core contraction increases. The outward flow of the released gravitational energy produces a temperature gradient and the central temperature increases during the speedup until it reaches about 1.2×10^{8}°K at point 4 (the central density is now more than 10^{5} g/sec). At this stage the energy production in the center of the core due to the $3\alpha\rightarrow C$ conversion (Sec. 8) becomes important. This central energy production, in a region in which the electrons are degenerate, now leads to a very fast expansion of the core which continues until the electrons are again nondegenerate (density less than 10^{4} g/sec). This is reflected in a fairly sudden jump from point 4 to point 5 in Fig. 4 (the core mass q is about 0.5 at this stage). Finally, in its evolution from point 5 toward point 6, the star has two steady nuclear energy sources, the $3\alpha\rightarrow C$ conversion near the center of the core and the H−He conversion in the shell outside the core.

The calculations, whose results I have just described, use a number of rather drastic simplifying approximations. The numerical results are thus not yet very accurate, but the semiquantitative agreement with observation is already quite remarkable. Another

[27] Arp, Baum, and Sandage, Astron. J. **58**, 4 (1953); A. R. Sandage, Mem. roy. sci. Liége **14**, 254 (1954); H. C. Arp, Astron. J. **60**, 317 (1955).

[28] A. R. Sandage and M. Schwarzschild, Astrophys. J. **116**, 463 (1952); F. Hoyle and M. Schwarzschild, Astrophys. J. Suppl. Ser., **2**, 1 (1955).

[29] The change in slope at point 2 is due to the onset of convection in the outermost envelope of the star.

word of warning: Even the qualitative features of the evolutionary track of an individual star, after it leaves the main sequence, are quite sensitive to the star's mass and the development of a star of more than twice the solar mass is probably rather different[30] from that of globular cluster stars. Nevertheless, we have both observational and theoretical qualitative data which indicate that younger and more massive stars in population *I* also evolve away from the main sequence towards larger luminosities and radii (red giant region). We cannot, of course, have any direct observational evidence for the presence of the nuclear reactions, described in Sec. 8, in the interior of stars. Nevertheless, anomalous abundances of various elements and isotopes in the surface of certain types of red giant stars at least hint at the formation of C^{12} to Ne^{20} (and possibly also of some of the heavier elements).

10. STELLAR EXPLOSIONS

I would like to conclude with two speculative ideas on the possibilities of stellar explosions; i.e., thermonuclear reactions which do not proceed on a long time scale, but on a very short one. The first one has to do with the expanding associations of gas and dust, mentioned in Sec. 5. Such an association seems to be a dynamic unit, containing a mass of a few hundred $M_{\odot}$ or more, and has quite a large amount of kinetic energy stored in its high expansion velocity. The problem is, what was the original energy source which fed this enormous expansion?

The most spectacular of various attempts at an explanation of this phenomenon is the following.[31] Assume that the original gas mass contracted under very special circumstances, for instance, by having very little angular momentum initially and by having density fluctuations in just the right way so that the whole thing fell in at a rapid rate. It heated up as it contracted, but had enough inwardly directed momentum so that it overshot the point where the first thermonuclear reaction would ordinarily stop the contraction. An appreciable fraction of the hydrogen in the central regions of this contracting gas mass might thus be converted into helium very suddenly. The enormous amount of energy produced raises the central pressure, which finally overcomes the inwardly directed momentum and an explosion (fast expansion) results. Since the exploding region is surrounded by a gas mass of very large radius, the original explosion would probably not be seen in terms of visible light. This explosion would eventually lead to a spherical expanding shock wave and bright stars might be formed out of the gas in a region near the shock front.[32]

The above hypothesis is, at the moment, highly

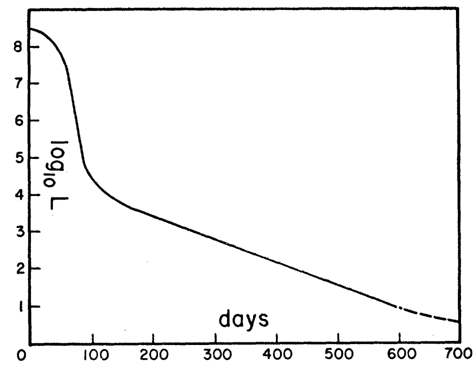

FIG. 5. The (schematic) light curve of a supernova of Type I. *L* is the luminosity in arbitrary units, plotted against time (in days after the initial eruption).

speculative, but it also serves as an introduction to one part of the other hypothesis I want to talk about. This has to do with the 55-day half-life of the light curve of supernovae of Type I and with the fission decay of Cf^{254} with the same half-life. In Fig. 5, the life history of the logarithm of the luminosity of a supernova, after it has first erupted, is shown. There is an enormous peak for the first 100 days or so, and then there is a very peculiar "tail" which, total energy-wise, is only about 10^{-3} of the original hump. This tail is an exponential curve for about 600 days with a 55-day half-life. The same half-life is found among all supernovae of this type (Type I). One has little direct observational evidence for what happens afterwards but, as you will hear from Professor Morrison in his talk on the origins of cosmic rays, there is at least indirect evidence that 1000 years later, in the Crab nebulae, there still is something or other that gives off energy. Thus, the contribution of the "Cf^{254} decay" is just a tiny part in quite a long and complicated light curve. It is, nevertheless, very spectacular to find a pure exponential decay for a period of over 10 times the half-life.

Previous theories on supernovae all had the one essential thing in common. One starts with the core of the star composed to a large extent of the most stable nuclei, the iron group. Then it is argued that, since this is the most stable possibility, any further nuclear reactions can only absorb energy. This, however, can lead to a collapse in the following way. If there is a nuclear process which is not only endothermic, but whose rate increases with density, then this will certainly result in collapse. First there is some energy loss, then the star contracts a bit, then its density goes up and there is a higher rate for the reaction, and so on. There are various kinds of such theories, but that is the essence of them. The one that is being investigated the most and works out the best is Gamow and Schönberg's[33] Urca process.

[30] R. J. Tayler, Astrophys. J. **120**, 332 (1954).
[31] Unpublished work by J. F. Bird (Cornell University), following a suggestion by T. Gold.
[32] J. H. Oort and L. Spitzer, Astrophys. J. **121**, 6 (1955); M. P. Savedoff and J. Greene, Astrophys. J. **122**, 477 (1955).
[33] G. Gamow and M. Schönberg, Phys. Rev. **59**, 539 (1941); also G. Gamow (unpublished work).

It was fairly easy to see how the core of a star could collapse suddenly. What was not so easy to see was how one could get an explosion out of a collapsing star. This is where the Cal. Tech. group came in.[34] They observed that only the core of the star need be entirely composed of the most stable nuclei. Outside of the core, say the outer half, there will undoubtedly be some iron, but this "mantle" will also contain lighter elements with a potentially large store of nuclear energy. Then, as the core suddenly collapses, the outer mantle will also begin to shrink quite rapidly and will heat up. Like in the other story I just told you, the hope is that the inwardly directed momentum during the collapse of this mantle will be large enough so that one gets a large rate of thermonuclear reactions before the contraction is brought to a halt. The star will then blow up and, if the mechanism was right, it will have put quite a bit of energy into the expanding cloud.

A much more specific part of the theory depends on the details of the chemical composition of this mantle and must explain the observed 55 day half-life. Briefly, the Cal. Tech. group's theory assumes that there occur roughly equal proportions of hydrogen, helium, and the elements from C to Ne. Given this initial chemical composition and with the right cross-section values (which we are not quite sure about yet), neutrons are made in essentially the following way. First Ne^{21} is made by a (p,γ) reaction on Ne^{20}, and then neutrons come off from just the (α,n) reactions already discussed (Sec. 8) as going on in "ordinary" stars at about 10^8°K. This time, however, the reactions proceed very, very rapidly. Once neutrons are made, they can be captured by nuclei in the iron group. It is possible to build all the way up to nuclei with $A \sim 270$ by alternating β decays with the neutron captures. When the whole star explodes, at least some of the products will have alpha decayed down to Cf^{254} which has a fission life of just the right time and a very large energy release per particle. Many quantitative aspects of the "Cal. Tech. theory" still remain to be tested, but it already seems like a very promising idea.

[34] Burbidge, Hoyle, Burbidge, Christy, and Fowler, Phys. Rev. **103**, 1145 (1956).

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