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TEMPERATURE AND DENSITY CONDITIONS FOR NUCLEOGENESIS BY FUSION PROCESSES IN STARS

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Valiant efforts are being made in many countries in an attempt to produce terrestrially a self-sustaining fusion process among atomic nuclei, principally among the isotopes of hydrogen. These efforts are encouraged by the sure knowledge that fusion reactions are taking place in stars and that the source of stellar energy is just the energy released in exothermic nuclear reactions. In stars, the containment problem, which is so difficult to solve on a terrestrial scale, has been solved automatically by the large mass of these objects. Gravitational forces, which increase as the square of the stellar mass, hold the interacting material together without the necessity of a containing wall. These gravitational forces are independent of temperature while the atomic forces which bind the structure of container walls are not. The conversion of gravitational potential energy into thermal kinetic energy on condensation of a star from the interstellar medium supplies the high temperatures necessary to initiate the fusion reactions. The energy release from these reactions makes them self-sustaining until the nuclear fuel is exhausted. In addition, this energy release leads to the development of internal pressure which stabilizes the star against gravitational collapse. This stability lasts for the relatively long periods necessary to consume the interacting nuclei. The burning hydrogen in the sun has lasted for five billion years and will last for at least as long in the future.

Stars can thus be considered as gravitationally stabilized fusion reactors which release energy through the conversion of one form of nuclear matter into another. Nuclear energy release demands nuclear transmutation and thus nucleogenesis. It is this aspect of the problem which is treated in this paper with emphasis on the temperatures and densities necessary for stellar nucleogenesis. Stellar nucleogenesis has come to be of considerable interest in various scientific disciplines, nuclear physics, geophysics, and astrophysics, because it provides a possible mode of synthesis from

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hydrogen of the heavier elements which are found in that part of the universe on which we can make observations.

Element synthesis in stars is an alternative to the theory of primordial synthesis (Gamow, Alpher, Herman)[1] during an early, high temperature, condensed phase of the expanding universe. There are considerable difficulties in the theory of primordial synthesis arising in part from the instability of the "missing links" in the synthesis chain at atomic mass five and mass eight. It is true that these difficulties are not insuperable (Hayashi and Nishida)[2] if it is assumed that in the early epoch of the universe the conditions of temperature and density were similar to those in the center of stars. However, experimental evidence in astrophysics has accumulated over the past few years in support of the belief that elements have been and are still being synthesized in stars. The products of any primordial synthesis have in any case been seriously modified by nuclear processes in stellar interiors. On the other hand, it is possible to develop in some detail the point of view that the Galaxy in which we are located, the Milky Way, formed originally from practically pure hydrogen and that the heavier elements from helium to uranium were produced in the original stars and succeeding generation of stars which have formed and evolved during the history of the Galaxy. On this point of view the sun is a second or third generation star whose formation was preceded by at least several billions of years of stellar evolution and element synthesis. There is astrophysical evidence that the oldest stars now observable have envelope material which has not mixed with the interior and which may be primordial or at least pregalactic. This material is indeed practically pure hydrogen with the order of at most 1 percent of the heavy element abundance found in the solar system.

Stellar nucleogenesis implies that there is an interchange of material between stars and the interstellar medium of gas and dust. Astronomical observations confirm that matter is given off by stars, both slowly and explosively, and that new stars are continually forming from the interstellar material. Star formation occurs primarily in the spiral arms of the Galaxy which contains practically all of the galactic gas and dust. Recent radio observations have shown that this gas and dust is being replenished by material moving rapidly (10^7 cm/sec) out from the galactic nucleus in the galactic plane at a rate (van den Bergh)[3] just necessary to make up for that lost by star formation which is approximately one solar mass per year. This material is probably ejected by giants, novae, and supernovae in the core and must be focused into the galactic plane in some way, perhaps by magnetic forces.

The first stars in the galaxy condensed then from practically pure hydrogen. Second and later generation stars contained some, but never very much, heavier debris from previous stars. In either case the events which took place were much the same. As the stellar material contracted over a period of the order of 10^8 years the central temperature and pressure rose from the conversion of gravitational potential energy into thermal kinetic and radiation energy. When the central temperature reached $\sim 10^7$ degrees absolute and the density reached ~ 100 grams/cm^3 the hydrogen began to interact directly through the so-called pp-chain or catalytically through the CNO or "snow" cycle. The latter cycle occurs only if the star contains the isotopes C^{12} or O^{16} produced in helium burning to be discussed later. Details of the pp-chain and the CNO-cycle have been recently discussed (Fowler; Burbidge, Burbidge, Fowler, and Hoyle)[4]. These discussions cover and give references to recent work on the pp-chain by Holmgren and Johnson at the Naval Research Laboratory and on the CNO-cycle by Lamb and Hester at UCRL, Livermore, and by Tanner, Pixley, and Hebbard at the California Institute of Technology. Both processes result in the conversion $4H^1 \rightarrow He^4$ with the release of 26.7 Mev or 4.3×10^{-5} ergs of energy from the small fractional difference (0.7%) between the mass of the helium atom and that of four hydrogen atoms. In general, only a few percent of the energy escapes from the star in the form of neutrinos produced in the reactions. The one exception, in which the pp-chain precedes through the energetic neutrino emitter, B^8, has been discussed in the first reference just cited. If such energetic neutrinos are emitted by the sun, they will have a flux $\lesssim 2 \times 10^{10}$ neutrinos/cm^2-sec at the earth's surface and they may prove to be detectable through observations on the $Cl^{37}(\nu,\beta^-)A^{37}$ reaction employing the techniques developed by R. Davis, Jr. at Brookhaven and Savannah River.[5]

From the standpoint of nucleogenesis the pp-chain is important because it is a mechanism by which pure hydrogen can be converted into helium. The CNO-cycle is important because starting with C^{12} and/or O^{16} produced in helium burning, the following isotopes are produced by successive proton captures: C^{13}, N^{14}, N^{15}, and O^{17}. These reach equilibrium abundances as the hydrogen is catalytically converted into helium and survive after the hydrogen is exhausted. The catalytic action arises from the fact that N^{15} and O^{17}, on capturing a proton, emit a He^4 nucleus plus C^{12} and N^{14} respectively. The N^{15} also produces some O^{16} by simple capture of hydrogen. Thus, the original nuclei are reproduced and the chain of reactions can occur over and over again while processing hydrogen into helium. This is in marked contrast to the fate of Li, Be, and B isotopes which are consumed in hydrogen interactions to form He^4. Thus, Li, Be, and B are not produced in the main-line of stellar nucleogenesis and their great rarity (Li, Be, B $\sim 10^{-5}$CNO) can be attributed to this fact. High energy spallation processes in the surfaces of stars may account for the low abundance which is observed for these elements.

At the central temperature, $T \sim 10^7$ degrees the most probable kinetic energy of interaction is $kT \sim 1$ kev. However, the interacting nuclei are all positively charged and nuclear processes can occur only after penetration of the repulsive electrostatic potential barriers. These barriers are much greater in energy than 1 kev, so classically, penetration could not occur at all, and it does so only through the quantum mechanical wave properties of the interacting particles. Even so, the penetration factor increases rapidly with energy and the interactions effectively occur far out on the tail of the Maxwell-Boltzmann distribution of particle energies. The effective interaction energy at which the interactions most probably occur is given by

$$E_0 = 1.22\ (Z_1^2 Z_0^2 A T_6^2)^{1/3}\ \text{kev}$$

where Z_1, Z_0, and $A = A_1A_0/(A_1+A_0)$ are the charges and reduced mass of the interacting particles and T_6 is the temperature in units of 10^6 degrees. As a rough rule, E_0 ranges from 5 to 25 times kT depending on the charges and the temperature. For neutrons the charge is zero and the above expression cannot be employed; instead, E_0 is just equal to kT.

The density at which the nuclear processes occur depends on a variety of factors. The rate of the usual two-body nuclear reaction depends on the square of the density; for the rarer three-body case the rate depends on the cube of the density. Hydrostatic equilibrium between internal pressure forces and gravitational forces along with the gas laws and heat transport equations are sufficient to determine the density except under explosive conditions when dynamic effects must be taken into account. The important point is that once a given nuclear "fuel" has been consumed, a star can gravitationally develop the higher densities and temperature necessary to cause the "ashes" to interact.

As long as a hydrogen burning star has not consumed too much of its hydrogen and retains approximately its original homogeneous composition, it will remain on the main sequence in the Herzsprung-Russell diagram in which the observed luminosity of a star is plotted against its observed surface color or temperature (not central temperature!). The main sequence is an approximate one-to-one correspondence in these observables for homogeneous stars of any composition, the massive, bright stars being blue in color and the smaller, less brilliant stars being red.

Thus, in the main sequence stage of stellar evolution, hydrogen is gradually converted into helium. The density, temperature, most probable energy, and effective energy at which this occurs are given in Table I. This table also contains similar entries for additional processes now to be described.

Eventually, the hydrogen "fuel" at the center of the star is exhausted and is replaced by the He^4 "ash." The doubly charged helium does not burn at 10^7 degrees or even somewhat above, and so energy generation ceases except in a thin shell surrounding the helium core. This shell now contains the hottest hydrogen in the star. As indicated in Table I, the shell temperatures reach 3×10^7 degrees while the density is somewhat less than central densities being of the order of 10 grams/cm^3. At this point in the star's history, gravitational forces again take over, the core contracts and develops higher temperatures and densities. The increase in radiation from the core heats up the outer envelope and causes it to expand greatly, the surface area increases considerably and permits the surface temperature to drop and still radiate the energy produced in the hydrogen burning shell. The star thus goes into the red giant stage of stellar evolution which has been extensively studied by Hoyle and Schwarzschild.[6]

In time, the central helium reaches temperatures of $\sim 10^8$ degrees and densities of $\sim 10^5$ grams/cc. Under these conditions the He^4 begins to interact essentially through a two stage three-body process which has been studied theoretically by Salpeter[7] and Hoyle[8], and experimentally by Cook, Fowler, Lauritsen, and Lauritsen.[9] This process can be designated schematically by $3He^4 \rightleftharpoons C^{12*} \rightarrow C^{12}$ where C^{12*} is an excited state at 7.65 Mev in C^{12} which reaches an equilibrium concentration in the hot helium and from time to time emits gamma radiation or electron-positron pairs to the ground state of C^{12}. The overall result is the production of carbon from helium. In addition, the C^{12} can capture a free He^4 to form O^{16} which in turn can capture another He^4 to form Ne^{20}. On the basis of present estimates concerning reaction rates, C^{12}, O^{16}, and Ne^{20} will be produced in equal amounts within an order of magnitude by the time the He^4 is exhausted. This is in agreement with their observed cosmic abundances of $C^{12}:O^{16}:Ne^{20} \approx 1:6:2$.

On exhaustion of the helium, still higher central temperatures and densities result, and if the star remains stable and does not come to a catastrophic end at this stage, then the carbon, oxygen, and neon will begin to interact to form still heavier nuclei. The interaction consists mainly of exchange of He^4 nuclei or alpha particles and has been designated as the α-process by Burbidge, Burbidge, Fowler, and Hoyle.[4] Little is known concerning the rates of such interactions and this should prove a fruitful field of research for heavy ion accelerators now in operation. It can be estimated that the α-process occurs at temperatures near 2×10^9 degrees and densities near 10^6 grams/cm^3. From the standpoint of nuclear physics, it is clear that this sequence of successive burning of heavier and heavier nuclei will eventually terminate at the iron group nuclei which are the most "stable" nuclei in the sense that the internal neutron-proton energies are at a minimum and their binding energies are at a maximum in absolute magnitude. Both heavier and lighter nuclei have higher internal energy content and are less "stable" in this sense than the iron group nuclei. The shape of the iron group peak in the cosmic abundance curve is in good agreement (Burbidge, Burbidge, Fowler, and Hoyle)[4] with the expected equilibrium distribution at $\rho \sim 10^8$ grams/cm^3 and $T \sim 4 \times 10^9$ degrees. In Table I, the process is designated as the equilibrium or e-process.

The α-process and the e-process probably occur at a rapidly evolving or even explosive stage of stellar evolution. It has been suggested (Burbidge, Burbidge, Fowler, and Hoyle)[4] that the collapsing core of a star in its terminal stages as a red giant or in its final catastrophic supernova stage is a possible site for such processes. The collapse of the core is brought about by the fact that no further generation of nuclear energy occurs after the iron group nuclei are produced. Gravitational contraction takes place unimpeded. The explosion is actually speeded up in the inner regions of the core by the refrigerating action of nuclear processes which transfer the iron group nuclei back into lighter nuclei with the absorption of energy.

The implosion of the core removes the underlying support of the envelope material of the star which contains unevolved nuclear fuel capable of releasing large amounts of energy on being raised to high temperature. The gravitational collapse of the envelope material does just this. The energy release by the nuclear reactions in the envelope material further raises its temperature, the collapse is reversed by expansion of the material and all or part of the envelope material and probably even a portion of core material is blown out from the star at high velocity. The result is observed astronomically as the occurrence of a supernova in which a star is observed in a very short interval to flare up to many times its previous luminosity and to eject a large fraction of its mass into space.

The supernova event is certainly the most spectacular of the ways in which stars eject nuclei which they have synthesized into interstellar space. It is believed that considerable mass loss also occurs less violently during the giant stage of stellar evolution. In any case, the new material mixes with the "primordial" hydrogen and may eventually condense with it into what we have referred to above as a second generation star. On the onset of hydrogen burning, the CNO-cycle becomes operative as described above and C^{13}, among other nuclei, is produced and survives as one of the catalysts in the cycling of hydrogen into helium. In addition, if the temperature is high enough, Ne^{21}, Ne^{22}, and Na^{23} are produced in a NeNa-cycle starting with Ne^{20}.

The CNO-cycle and NeNa-cycle occur in hydrogen burning during the main sequence stage of the second generation star. Eventually, the hydrogen is exhausted and the carbon, nitrogen, oxygen, neon, and sodium isotopes remain mixed with the helium in the contracting core as the star goes into its red giant stage. Now, a new set of helium burning reactions is possible and the most interesting of these are the interactions of C^{13} and Ne^{21} with He^4. These interactions result in the emission of neutrons. (Greenstein; Cameron; Fowler, Burbidge, and Burbidge)[10]

The neutrons are preferentially captured by heavy nuclei. If a small number of iron-group nuclei are contained in the material from which the second generation star has condensed, then these nuclei will capture the neutrons to build still heavier nuclear forms. Since the neutron is not charged, the effective temperature will just be kT or about 10 kev for a red giant central temperature of 10^8 degrees. In general, the C^{13} and Ne^{21} produced from C^{12} and O^{16} are the order of one hundred times as abundant as the iron group nuclei so that approximately 100 neutrons are made available per iron group nucleus and this is sufficient to produce heavy nuclei in the range $60 \lesssim A \lesssim 200$. The rate of red giant evolution is relatively slow and the average interval between neutron captures for a given nucleus extends over the range 10 to 10^5 years. Even for the lower limit, the interval is long enough for most beta decay processes to occur in between neutron captures when a nucleus unstable to electron-neutrino emission is produced in the capture chain. Thus, the capture path remains close to the line of stable nuclei in the charge-mass or Z, A plane. Some nuclear species are by-passed in such a neutron capture process. These are in general the light, proton-rich isotopes of the elements as well as the heavy, neutron-rich isotopes which are preceded by a beta-unstable, lighter isotope which decays to the next element in the periodic table. Thus, only certain of the nuclear species can be produced by neutron capture at a rate slow compared to beta decay in the red giant stage of stellar evolution.

In order to synthesize the heavy, neutron-rich isotopes which are by-passed in the process just described, it is clearly necessary to have a situation in which an intense flux of neutrons is made available and neutron captures occur at a rate which is rapid compared to beta decay. Again, it would seem indicated that supernovae may provide such a situation. The envelope material is heated by implosion, hydrogen burning is initiated, additional nuclear heating results until helium reactions with C^{13} and Ne^{21} occur very rapidly. These reactions provide neutrons just as in red giant stars but now at a fast rate compared to beta decay and the synthesis process actually involves nuclear species having a neutron-proton excess some ten units greater than for normal nuclei. After the supernova event, these nuclei decay to their stable isobars which will just be the heavy, neutron-rich isotopes of the elements. Burbidge, Burbidge, Fowler, and Hoyle[4] estimate densities of 10^5 grams/cm^3 and temperatures of 10^9 degrees in the supernova envelopes and a neutron flux of 10^{32} neutrons/cm^2-sec.

In addition, there will certainly be some free hydrogen at the high temperature of the supernova envelope material. Coulomb barrier penetration factors for protons will be small but not zero and some synthesis of the light, proton-rich isotopes of the elements will also occur. It is a very satisfactory point of fact that all of these light isotopes are indeed very rare compared to the heavier forms.

As noted previously, Table I contains a tabulation of the conditions under which the various fusion processes occur. It will be seen that the central temperatures and densities show a steady increase with the evolutionary advance of a star from the main sequence, through the red giant, to the supernova stage. This is in keeping with the general point of view that such a procedure is essential if heavier and more highly charged nuclei are successively to be synthesized from the lighter ones starting originally with a universe or a Galaxy of pure hydrogen.

TABLE I. CONDITIONS OF TEMPERATURE AND DENSITY FOR FUSION PROCESSES IN STARS

Stellar Stage and Nuclear Processes	Density gram/cc	Temperature degrees abs.	kT kev	Effective energy (kev)
MAIN SEQUENCE STAGE				
$4H^1 \xrightarrow[CNO]{pp} He^4$	100	10^7	1	5 (+)
		2×10^7	2	30 (+)
RED GIANT STAGE				
$4H^1 \rightarrow He^4$ (shell)	10	3×10^7	3	50 (+)
$3He^4 \rightarrow C^{12}$, etc.(core)	10^5	10^8	10	150 - 300 (+)
neutron capture (slowly)				10 (n)
SUPERNOVA CORE				
alpha process	10^6	2×10^9	200	3000 (+)
equilibrium process	10^8	4×10^9	400	400(n)to 3000(+)
SUPERNOVA ENVELOPE				
neutron capture(rapidly)	10^5	10^9	100	100 (n)
proton capture (rare)				2000 (+)

(n) indicates the effective energy(kev) for neutrons.
(+) indicates the effective energy(kev) for charged particles.

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