Energy Production in Stars

In several recent papers,[1–3] the present author has been quoted for investigations on the nuclear reactions responsible for the energy production in stars. As the publication of this work which was carried out last spring has been unduly delayed, it seems worth while to publish a short account of the principal results.

The most important source of stellar energy appears to be the reaction cycle:

$$\begin{aligned} &C^{12}+H^1=N^{13}\ (a),\ N^{13}=C^{13}+\epsilon^+\ (b)\\ &C^{13}+H^1=N^{14}\ (c)\\ &N^{14}+H^1=O^{15}\ (d),\ O^{15}=N^{15}+\epsilon^+\ (e)\\ &N^{15}+H^1=C^{12}+He^4\ (f).\end{aligned} \qquad (1)$$

In this cycle, four protons are combined into one α-particle (plus two positrons which will be annihilated by two electrons). The carbon and nitrogen isotopes serve as catalysts for this combination. There are no alternative reactions between protons and the nuclei $C^{12}C^{13}N^{14}$; with N^{15}, there is the alternative process

$$N^{15}+H^1=O^{16},$$

but this radiative capture may be expected to be about 10,000 times less probable than the particle reaction (f). Thus practically no carbon and nitrogen will be consumed and the energy production will continue until all protons in the star are used up. At the present rate of energy production, the hydrogen content of the sun (35 percent by weight[4]) would suffice for 3.5×10^{10} years.

The reaction cycle (1) is preferred before all other nuclear reactions. Any element *lighter* than carbon, when reacting with protons, is destroyed permanently and will not be replaced. E.g., Be^9 would react in the following way:

$$\begin{aligned} &Be^9+H^1=Li^6+He^4\\ &Li^6+H^1=Be^7\\ &Be^7+\epsilon^-=Li^7\\ &Li^7+H^1=2He^4.\end{aligned}$$

Therefore, even if the star contained an appreciable amount of Li, Be or B when it was first formed, these elements would have been consumed in the early history of the star. This agrees with the extremely low abundance of these elements (if any) in the present stars. These considerations apply also to the heavy hydrogen isotopes H^2 and H^3.

The only abundant and very light elements are H^1 and He^4. Of these, He^4 will not react with protons at all because Li^5 is unstable, and the reaction between two protons, while possible, is rather slow[5] and will therefore be much less important[6] in ordinary stars than the cycle (1).

Elements heavier than nitrogen may be left out of consideration entirely because they will react more slowly with protons than carbon and nitrogen, even at temperatures much higher than those prevailing in stars. For the same reason, reactions between α-particles and other nuclei are of no importance.

To test the theory, we have calculated (Table I) the energy production in the sun for several nuclear reactions, making the following assumptions:

(1) The temperature at the center of the sun is 2×10^7 degrees. This value follows from the integration of the Eddington equations with any reasonable "star model."[4] The "point source model" with a convective core which is a very good approximation to reality gives 2.03×10^7 degrees.[7] The same calculation gives 50.2 for the density at the center of the sun. The central temperature is probably correct to within 10 percent.

(2) The concentration of hydrogen is assumed to be 35 percent by weight, that of the other reacting element 10 percent. In the reaction chain (1), the concentration of N^{14} was assumed to be 10 percent.

(3) The ratio of the average energy production to the production at the center was calculated[7] from the temperature-density dependence of the nuclear reaction and the temperature-density distribution in the star.

TABLE I. *Energy production in the sun for several nuclear reactions.*

REACTION	AVERAGE ENERGY PRODUCTION ϵ(erg/g sec.)
$H^1+H^1=H^2+\epsilon^++f.$*	0.2
$H^2+H^1=He^3$	3×10^{16}
$Li^7+H^1=2He^4$	4×10^{14}
$B^{10}+H^1=C^{11}+f.$	3×10^5
$B^{11}+H^1=3He^4$	10^{10}
$N^{14}+H^1=O^{15}+f.$	3
$O^{16}+H^1=F^{17}+f.$	10^{-4}

* "$+f.$" means that the energy production in the reactions following the one listed, is included. E.g. the figure for the $N^{14}+H^1$ includes the complete chain (1).

It is evident from Table I that only the nitrogen reaction gives agreement with the observed energy production of 2 ergs/g sec. All the reactions with lighter elements would give energy productions which are too large by many orders of magnitude if they were abundant enough, whereas the next heavier element, O^{16}, already gives more than 10,000 times too small a value. In view of the extremely strong dependence on the atomic number, the agreement of the nitrogen-carbon cycle with observation is excellent.

The nitrogen-carbon reactions also explain correctly the dependence of mass on luminosity for main sequence stars. In this connection, the strong dependence of the reaction rate on temperature ($\sim T^{18}$) is important, because massive stars have much greater luminosities with only slightly higher central temperatures (e.g., Y Cygni has $T=3.2\times10^7$ and $\epsilon=1200$ ergs/g sec.).

With the assumed reaction chain, there will be no appreciable change in the abundance of elements heavier than helium during the evolution of the star but only a transmutation of hydrogen into helium. This result which is more general than the reaction chain (1) is in contrast to the commonly accepted "Aufbauhypothese."

A detailed account of these investigations will be published soon.

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[2] J. Oppenheimer and R. Serber, Phys. Rev. **54**, 540 (1938).
[3] G. Gamow, Phys. Rev. (in print).
[4] B. Strömgren, Ergebn. d. Exak. Naturwiss. **16** (1937).
[5] H. Bethe and C. Critchfield, Phys. Rev. **54**, 248 (1938).
[6] Only for very cool stars (red dwarfs) the H+H reaction may become important.
[7] The author is indebted to Mr. Marshak for these calculations.