NUCLEOGENESIS IN STARS

2. STELLAR SYNTHESES OF THE ALPHA-PARTICLE NUCLEI HEAVIER THAN ^{20}Ne

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Presented by Takeo Hatanaka

Many authors [1–3] discussed the nuclear reactions which can go on in stellar interiors up to the point where the helium has been exhausted by the $3\alpha \rightarrow {}^{12}$C and subsequent (α, γ) reactions. Beyond this stage stars contract again and heat up until further thermonuclear reactions begin to occur inside their cores. To explain the cosmical abundances of α-particle nuclei, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}A, and ^{40}Ca, Burbidge, Burbidge, Fowler and Hoyle [4] proposed the so-called α-process. The first and most important reaction in this process is ^{20}Ne (γ, α) ^{16}O due to its small negative Q-value. Once α-particles have been emitted, the nuclei heavier than ^{20}Ne can be built by successive (α, γ) reactions. In very hot stars consisting of ^{12}C, ^{16}O and ^{20}Ne, ion-ion reactions, such as $^{12}C+{}^{12}C \rightarrow {}^{20}Ne+\alpha$ and $^{12}C+{}^{16}O \rightarrow {}^{24}Mg+\alpha$, must also be taken into account as a possible α-particle source.

The purpose of this note is to investigate the stellar conditions, that is, the temperature, the density and the duration of time which are necessary to explain the observed abundances of α-particle nuclei by the above process. Before doing this, various nuclear reaction rates were calculated by the well-known procedures [4]. In calculating the (α, γ) reaction rates for the nuclei heavier than ^{24}Mg, their atomic number dependence being the most important for our purposes, we can use the approximate cross-sections given by the statistical theory, because in such reactions excitation energies are so high that the resonant properties of individual levels are smeared out.

I. EQUILIBRIUM THEORY

To explain the abundances of α-particle nuclei heavier than ^{20}Ne by the equilibrium theory, the temperature $\sim 10^{10}$ °K and the matter density 5×10^{8} g/cm^{3} are required. Under this condition the nuclear reaction times are of the order of 10^{-5} sec and it seems rather unlikely that we can find stellar outbursts which are rapid enough to assure the freezing-in of this established equilibrium.

II. SLOW SYNTHESES IN STELLAR CORES

The fastest ion-ion reaction, $^{12}C+{}^{12}C$, competes [5] with ^{20}Ne (γ, α) ^{16}O at the temperature $T \leqslant 2 \times 10^{9}$ °K with the density $\rho \simeq 10^{5}$ g/cm^{3}. When the central temperature of stars consisting of ^{12}C, ^{16}O and ^{20}Ne with the above density rises to about $6 \sim 7 \times 10^{8}$ °K, the $^{12}C+{}^{12}C$ reaction can be a main energy source of these stars with $100 \sim 1000$ times solar luminosities. At this temperature, however, the atomic number dependence of the (α, γ) reaction rates are too large to reproduce the cosmical abundances of α-particle nuclei heavier than ^{28}Si.

Alternatively, if the stellar cores consist of ^{20}Ne only, ^{20}Ne (γ, α) ^{16}O is a main α-particle source for the formation of the heavier nuclei. If ^{20}Ne (γ, α) ^{16}O and subsequent (α, γ) reactions are to be the energy sources of such stars, the central temperature near 1×10^{9} °K is required. This temperature is still too low to overcome the above difficulty.

III. RAPID SYNTHESES IN THE SUPER-NOVAE EXPLOSIONS

At higher temperature $T = 2 \sim 3 \times 10^{9}$ °K, the differences among the (α, γ) reactions become so small that it will be possible to explain the abundances concerned in terms of the α-process.

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At $\rho = 10^5$ g/cm^3 where the (α, γ) reaction rates are much greater than (γ, α) ones, the emitted α-particles are absorbed instantaneously by ^{12}C, ^{16}O or ^{20}Ne but they are hardly used for the formation of nuclei heavier than ^{28}Si. The result is not different from the case (II).

Our calculations, however, show that the abundances in question can be reproduced by taking the density $\rho \simeq 10^2$ g/cm^3, where the (γ, α) reaction rates are comparable to (α, γ) ones. At this temperature the reaction time for $^{20}Ne\ (\gamma, \alpha)\ ^{16}O$ is $10^{-2} \sim 1$ sec, while $10^3 \sim 10^7$ sec for the other (γ, α) reactions, and to explain the observed abundances it is necessary for such temperature to continue for a rather short time $1 \sim 10^2$ sec with a rapid heating-up and a subsequent cooling. Such stellar conditions could be realized in the supernovae explosions, as the time scale of implosion preceding the explosions is estimated to be of the order of 10^{-1} sec [4] and such high temperature will continue for $1 \sim 10^2$ sec.

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3. THE PRODUCTION OF ELEMENTS IN SUPER-NOVAE

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The following assumptions concerning super-novae will be employed in the present paper:

(i) The internal temperature is very high, exceeding 10^9 °K;

(ii) a frequency rate of ~ 1 per galaxy per 10^2 years;

(iii) the mass distributed in space $\sim 1 \odot$ per super-nova.

Taking $\sim 8 \times 10^9$ years for the age of the Galaxy gives a total of $\sim 8 \times 10^7$ super-novae over the whole history of the Galaxy, and $\sim 8 \times 10^7 \odot$ for the total mass distributed by them into space. Thus the fraction of the mass of the Galaxy that has experienced 'cooking' inside super-novae is of order 0·5%.

So long as temperatures in excess of 5×10^9 °K are not under consideration the general tendency of nuclear reactions inside stars is to increase the average binding energy per nucleon. This will become clear from the following examples:

At temperatures from about 10^7 to 5×10^7 °K in main-sequence stars hydrogen is transformed to helium, with an average binding energy of 7·07 MeV per nucleon. At temperatures from 10^8 to 2×10^8 °K in giants and super-giants, ^4He is transformed principally to ^{12}C, ^{16}O, and ^{20}Ne with an average binding energy of 7·98 MeV per nucleon. At temperatures of the order 10^9 °K, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}A, and ^{40}Ca are formed from the carbon, oxygen, and neon, the average binding thus rising to 8·55 MeV per nucleon, while at temperatures from 2×10^9 to 5×10^9 °K, ^{56}Fe and neighbouring nuclei are synthesized, yielding in average binding energy of 8·79 MeV per nucleon.

The first suggestion of the present paper is that the origin of the very high temperature elements (temperatures above 10^9 °K) is to be associated with super-novae. It is an immediate encouragement to this point of view that the proportion of the mass of the Galaxy that has been processed in this way would appear to amount to a moderate fraction of a per cent, exactly as is required by observation. Moreover the *relative* abun-