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SILICON BURNING AND THE SYNTHESIS OF COSMIC-RAY NUCLEI

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ABSTRACT

The source abundances of the cosmic-ray nuclei of atomic number $14 \leq Z \leq 28$ are found to be in good agreement with calculations based on the quasi-equilibrium silicon-burning process. The low-density environment appropriate for cosmic-ray nucleosynthesis differs from that required for synthesis of the observed solar-system ("universal") abundances in a way which is consistent with the shock acceleration model for the supernova origin of the nuclei observed in both abundance measurements.

The quasi-equilibrium silicon-burning mechanism has been successfully applied[1,2] to the explanation of the solar abundances of the nuclei with atomic numbers in the range $14 \leq Z \leq 28$. This mechanism operates when Si^{28} in a free bath of alpha particles is heated to temperatures above 3×10^9 K, with the heavier element abundances being linked to that of Si^{28} primarily through a chain of (α,γ) reactions that are in equilibrium with the inverse reactions. At 4.4×10^9 K and silicon is rapidly burned with a time scale of < 1 sec; these time scales become compatible with that of the shock wave in a supernova[3] where the mechanism is believed to operate[4].

Supernovae have been recognized as possible sources of cosmic radiation for some time[5] and the model studied by Colgate and White[3] describes the acceleration of the outer layers of the supernova to relativistic energies. It, therefore, seems reasonable to attempt to ascribe the composition of cosmic radiation in the region from silicon through iron to silicon burning. The cosmic-ray composition is known to differ from that of the sun[6] even after corrections have been made for the passage of the radiation through interstellar material. In the following we find that those differences are not inconsistent with silicon-burning in an environment of lower density ($\rho \simeq 10^5$ g/cm^3) than that required to obtain agreement with solar abundance ($\rho = 10^7$ g/cm^3). This difference in density is completely consistent with the supernova shock-acceleration model[3].

If we confine our attention to cosmic-ray nuclei at relativistic energies where changes in energy are small, the flux $J_i(x)$ of i-type nuclei above any given energy after passing through x g/cm^2 of interstellar material is described by[5,7]

$$dJ_i(x)/dx = -J_i(x)/\lambda_i + \sum_{k>i} J_k(x)/\lambda_{ik} \qquad (1)$$

where λ_i is the mean free path for loss of i-type nuclei and λ_{ik} is the mean free path for production of i-type nuclei from (heavier) k-type nuclei.

It has been found[5] that the distribution of matter traversed is well represented by an exponential so that the observed flux j_i is found (within a constant factor) from

$$j_i = \int_o^\infty J_i(x) \exp(-x/x_o)\, dx \qquad (2)$$

This distribution is appropriate when a time equilibrium is established between the loss of cosmic rays by galactic escape (with mean free path x_o) and their production from a uniform continuous distribution of sources, but it is also approximately valid for a random distribution of discrete sources distributed within the galactic disc[8,9].

If we note that j_i is formally the Laplace transform with respect to $1/x_o$ of $J_i(x)$ and take the Laplace transform of Eq. (1) we find

$$J_i(0) = j_i/x + j_i/\lambda_i - \sum_{k>i} j/\lambda_{ik} \qquad (3)$$

so that the flux of i-type nuclei from the source is a linear combination of observed fluxes. Eq. (3) may also be obtained as the energy independent limit of the solutions of the equilibrium problem[10,11].

We have applied Eq. (3) to the observed cosmic-ray composition summarized by Shapiro and Silberberg[6]. The fragmentation mean-free-paths were calculated using the empirical cross-section formula of Rudstam[12] and that of Shapiro and Silberberg[6]. Differences between the results using the two formulae were not found to be significant for the nuclei of interest and the Rudstam formula was used in obtaining the cosmic-ray source composition shown by circles in Fig. 1. The observed composition used for these calculations is shown by crosses in the figure.

The value of x_o is customarily determined by the requirement that Li, Be and B are purely secondary nuclei. Using Eq. (3) and the fragmentation cross-sections of Yiou[13], this condition occurs for $x_o \simeq 5$ gm/cm^2. For this value, however, the source fluxes Cl, K, Sc, Ti and V become negative, implying that the observed fluxes should be increased by as much as three standard deviations for K and Sc. If we require that these fluxes be increased by no more than two standard deviations we find $x_o \leq 4$ g/cm^2 in calculating the results shown in Fig. 1. This lower value of x_o is also in better agreement with the composition of the nuclei with $30 \leq Z \leq 90$.[14]

The composition resulting from Si burning has been calculated from the results tabulated by Bodansky, Clayton and Fowler[2]. Within the range of environments studied by those authors, $3.6 \times 10^9 \leq T \leq 5.0 \times 10^9$ K and $10^6 \leq \rho \leq 10^9$ g/cm^3 best agreement with the cosmic-ray data is obtained for $T = 4.6 \times 10^9$ K, $\rho = 10^6$ g/cm^3 with the fraction of silicon remaining, $f = .15$; these results are shown in Fig. 1. The time scale for the burning is $t = 77$ msec. for this case.

For any temperature and density the comparable abundances of Fe and Si imply $.15 \leq f \leq .25$. However, the low abundances of elements in the region $15 \leq Z \leq 19$, a distinctive feature of the cosmic radiation, are obtained only for the lowest densities at a given temperature. The results are not highly sensitive to temperature within the above constraints. Since the time scale is a strong function of temperature, it is also poorly determined.

Calculations with $\rho \sim 10^7$ g/cm^3, the value used for comparison with the solar composition[1], result in abundances of S, Ar and Ca which are factors of 2, 3 and 6 larger, respectively, than those for $\rho = 10^6$ g/cm^3 shown in the figure. Even at 10^5 g/cm^3 the calculated sulphur abundance is more than one standard deviation above the cosmic-ray abundance suggesting that even lower densities might be appropriate.

For a supernova of about two solar masses, the theory of Colgate and White[3] predicts that an external mass fraction of $\sim 10^{-4}$ will be ejected as relativistic cosmic rays. The environment attained in these outer shells of the supernova is in excellent agreement with that which we find from the cosmic-ray composition.

We note that material burned rapidly at low density seems inappropriate to a post-supernova environment which would obtain in the vicinity of a pulsar.

A significant feature of the low density solution is that Ni^{56} can dissociate into Fe^{54} + 2p in this environment which is neutron rich relative to the solutions at higher density, free neutron to proton ratio being 1.7×10^{-4} here (vs. $\sim 10^{-8}$ at $\rho = 10^{8}\,g/cm^{3}$). Thus the dominant iron isotope produced is Fe^{54} rather than Fe^{56} resulting from the decay of Ni^{56} which is produced deeper in the supernova envelope. Since we have not attempted to exclude lower density solutions which might result in the direct production of Fe^{56}, the isotope structure of cosmic-ray Fe is not clearly determined. A large proportion of Fe^{54} in cosmic rays would affect the recently-suggested[15] technique for determining the age of the radiation by observing the effects of Mn^{53}, though not adversely since Mn^{53} would be the only quasi-stable isotope of Mn produced as a secondary from Fe^{54} fragmentation in interstellar hydrogen.

Insofar as the nuclei in the range $14 \leq Z \leq 28$ are concerned it seems possible to form a consistent model for their synthesis via the quasi-equilibrium silicon-burning mechanism in supernovae. The bulk of the material ejected is burned at high density and later accreted by stars such as the sun while the outer layers, burned at lower density, are accelerated to high energies and are observed as cosmic radiation. Postulating that the same mechanism is responsible for both samples of material clearly does not imply the same composition for both samples.

In fact the model would imply gradual changes in the cosmic-ray composition with energy since cosmic rays accelerated to different energies would experience nucleosynthesis in different environments. The observation of changes in cosmic-ray composition with energy eventually could provide a powerful experimental test of the model.

It should clearly be emphasized that the present work is confined to a very limited region of nuclear charge. The abundances of other nuclei in cosmic radiation, especially those with $6 \leq Z \leq 14$, could be highly relevant and remain unexplained by the present model. However, this being the first known attempt at a quantitative comparison of nucleosynthesis theory with cosmic-ray observations, we find the agreement obtained here encouraging.

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FIGURE CAPTION

Fig. 1: The abundance of elements extrapolated to the cosmic ray sources (solid circles) are compared with the results of silicon burning with $T = 4.6 \times 10^{9}$ K, $\rho = 10^{5}$ g/cm^3 and $f = .15$ (see text). Also shown are the observed cosmic-ray abundances (crosses). All abundances are normalized to that of silicon.

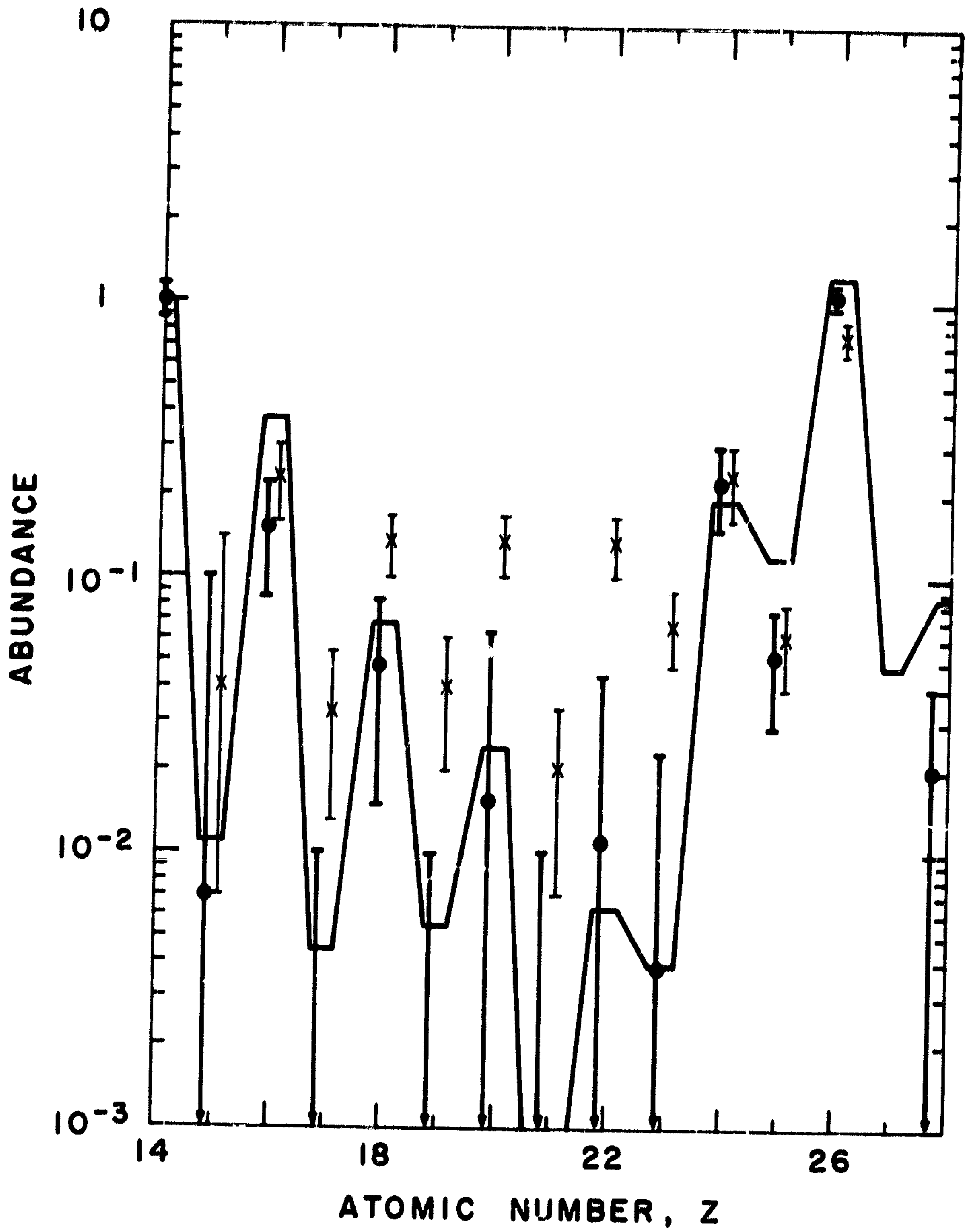

Fig. 1