SOURCES OF THE ULTRAHEAVY COSMIC RAYS

STEVEN H. MARGOLIS
McDonnell Center for the Space Sciences
Washington University
St. Louis, MO 63130 USA
and
J. B. BLAKE
Space Sciences Laboratory
The Aerospace Corporation
Los Angeles, CA 90009 USA

ABSTRACT

The suggestions that the source abundances cosmic ray nuclei heavier than Fe differ significantly from Solar System abundances are not well supported by the data without assuming preferential acceleration. The Solar System abundances of Pb and Bi are split into *r*-, standard *s*-, and cyclic *s-process* components; the apparent deficiency of Pb seen in the HEAO-3 HNE data might indicate an absence of Pb from the recycling *s-process*.

1. Introduction. The nuclei substantially heavier than Fe have been measured only relatively recently with electronic detectors (Fowler *et al.* 1983, Binns *et al.* (1984), and these experiments have yielded so far only results on even-Z elements or broad abundance groups in estimated charge. The calculations of Blake and Margolis (1981a) provided a selected set of standard propagations of Solar-like abundances ($26 \leq Z \leq 59$) which could be used to evaluate the experimental results in terms of *r*- and *s-process* contributions and the effects of preferential acceleration with a first ionization potential dependence (hereinafter FIPD). In this paper, propagation calculations of even heavier nuclei ($Z \geq 60$) are discussed in light of the now-published data in this range and other published analyses (Protheroe and Ormes, 1981; Blake and Margolis, 1981b; Brewster, Freier, and Waddington, 1983; Tsao *et al.*, 1983). The analysis presented here demonstrates that the simple picture of Solar abundances propagated according to models inferred from the lower-Z measurements does not account for the structure reported in the higher-Z abundances.

2. Calculations Of Propagated Abundances. The chemical and isotopic abundances of Anders and Ebihara (1982) provide a specific sample of nucleosynthesis in the Galaxy. These were propagated (a full description of the calculation appears in Margolis and Blake, 1985) to generate a set of abundances similar to what might be measured near the Earth, excluding the effects of Solar modulation. Figure 1 compares one such calculation, that for a 7 g cm^{-2} leaky box (shown as a solid line) with a composite data set (shown as isolated circles) assembled from the preliminary results of the HEAO-3 Heavy Nuclei Experiment (Binns *et al.*, 1981, 1984). Both sets of values have been normalized to 10^6 Fe nuclei, and the calculated values have been smeared with a Gaussian profile of width varying with charge in order to join the deconvolved lower charges to the reported resolution of the higher charges. For comparison, the dashed line in that figure displays, with the same normalization and smearing, the source abundances without propagation. In general, the patterns track reasonably well.

The plotting range necessary for displaying Figure 1 makes it an inconvenient form to use for most comparisons with observations, but such a display has a significant advantage over the more usual element group plots. The typical group plot illustrates the changing balance between secondary and primary elements resulting from propagation. One must remember that the comparisons to observation must be made not only in terms of the ratios of widely separated elements. The systematic effects of nucleosynthesis affect both kinds of ratios. The Solar System abundances, a known sample of cosmic matter, provide a definite, global normalization to the value of a single element. In the absence of any isotopic data, this normalization is all the more important. For example, elements near the Te-Ba peak do not change their abundances relative to Fe with propagation, but those at the Pt-Pb peak do. This contrast implies that the group ratio $(50 \leq Z \leq 56)/(Z = 26)$ is not a measure of propagation but of the most basic nucleosynthetic indicator: the abundance of *r*- and *s-process*

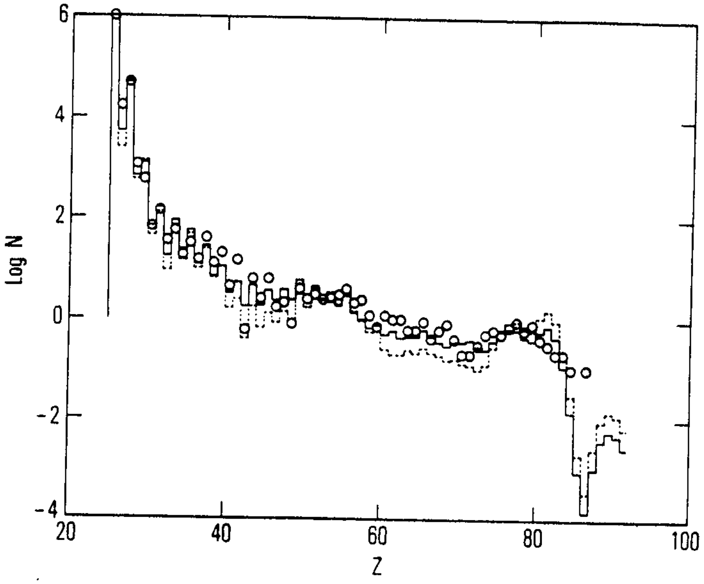

Figure 1. The circles represent a composite of preliminary results from the HEAO-3 Heavy Nuclei Experiment (Binns *et al.*, 1981, 1984). The dashed line shows the Solar abundances of Anders and Ebihara (1982) convolved with a Gaussian profile of varying width. The solid line shows the Solar abundances propagated through a 7 g cm^{-2} leaky box, also smeared.

material relative to that of the iron peak. In this respect, the data indicate that the cosmic ray source is consistent with the solar balance of those nucleosynthesis processes.

Although propagation does affect the observed abundances, removing the effects of a reasonable propagation model is probably sufficient. At least, the available data do not warrant more careful attention to such detail. It is not yet clear that any of the current experiments can recover a global normalization to Fe with the precision reported in a calculation. However, it is clearly worth considerable effort to obtain the best possible global abundance pattern from the experimental data. Important questions can be addressed with only minimal requirements on the charge resolution of an experiment.

3. Preferential Acceleration/Selection Effects. It is now standard procedure to consider selection effects in the cosmic ray chemical abundances based upon atomic properties of the element in question. The parameter usually chosen is the first ionization potential of the atom. A straight-line fit is made to a semi-log plot of the ratio of cosmic ray source abundances (derived from the data) to Solar System abundances *vs.* the ionization potential of the atom in question. This fit is then used to weight the source abundances which are input into a propagation calculation. Binns *et al.* (1984) question this approach, and argue that an equally good fit to their data is obtained with a step function rather than a straight line. They suggest that the discontinuity is an artifact caused by selecting Cl carbonaceous chondrites rather than C2 as the baseline for the Solar System abundances.

This is an interesting suggestion but there is considerable reason for regarding it with suspicion. First, at the sun and in planetary magnetospheres where individual acceleration events can be observed, preferential acceleration is ubiquitous. Second, the plot of the abundance ratio vs. first ionization potential continues to be ordered after exchanging C2 abundances for Cl abundances.

Difference in the ratio of *r-* to *s-process* abundances between cosmic rays and the Solar System can indicate either source differences or preferential acceleration. The question of preferential acceleration in the study of ultraheavy cosmic rays is so vexing because the *r-* and *s*-process peaks also have, on the average, significantly different first ionization potentials. However, selection effects should depend on the overall atomic physics of the atom and not simply the first ionization potential. Margolis and Blake (1983) noted that the influence of the second ionization potential disperses the predictions of preferential acceleration models in a manner consistent with the scatter of the observations about the straight-line fit. Although not perfect, such modifications are certainly the direction for further study. Without more knowledge of the nature of the cosmic ray source, it is difficult to make a meaningful improvement on the presently existing work.

4. Nucleosynthesis Considerations. It is very well known that the nucleosynthesis of the elements with $A > 60$ results largely from neutron capture processes; the *p-process* is responsible only for rare isotopes. In the analysis of ultraheavy cosmic ray data it is traditional to examine the paired abundance peaks which are due to neutron shell closure — Se and Sr, Te and Ba, and Pt and Pb — as an indicator of the relative abundance of the *r-* and *s-process* in the cosmic ray source(s). For (Te, Ba) and (Pt, Pb), the lower mass peak in the pair is largely the result of the *r-process*, and the upper one to the *s-process* nuclei. The heavier nuclei around Sr are mainly *s-process*, but the nuclei around Se show substantial contributions from both processes.

Implicit in these assignments is the assumption that each peak comes from a single nucleosynthetic site, at least once the contribution from the companion process is removed. However, in the case of the *s-process* peak at Pb, this assumption is incorrect. The *s-process* which fits the heavier Solar System isotopes up through ^{204}Pb underproduces the heavier Pb isotopes (Käppeler *et al.*, 1982; Ulrich 1983: although these references are recent and refer to the latest comprehensive work, this fact has been known for a long time.) The *s-process* terminates at ^{209}Bi because the next heavier nucleus, ^{210}Po, decays by emission back to ^{206}Pb. Therefore, with sufficient neutron exposure, all nuclei capture sufficient neutrons to join the quartet consisting of ^{206,207,208}Pb, and ^{209}Bi. The recycling process was described in detail by Clayton and Rassbach (1967). The important point for present purposes is that the site of the intense *s-process* exposure required to cause recycling may well not be the same as that which creates the *s-process* isotopes with $A \leq 204$ (Truran and Iben, 1977; Ulrich, 1983). Therefore, if the cosmic ray source were deficient in *s-process* material only from the recycling site, then the *r-process* and *s-process* nuclei at (Se, Sr) and (Te, Ba) would appear Solar, but at (Pt,Pb), Pb would be deficient.

Nucleus	Total Abundance	Normal *s-process*	Radiogenic *r-process*	Recycling *s-process*
^{206}Pb	0.603	0.180	0.12	0.30
^{207}Pb	0.650	0.176	0.10	0.37
^{208}Pb	1.838	0.402	0.06	1.38
^{209}Bi	0.144	0.016	0.12	0.01

Table 1. The nucleosynthetic origins of the nuclei affected by the cyclic *s-process*. The Total Abundance is taken from Anders and Ebihara (1982), and the Normal *s-process* from Käppeler *et al.*, (1982).

Given here is a zeroth-order decomposition of the Pb peak. The details can be found in Margolis and Blake (1985). It can be seen from the abundance values given in Table 1 that ≈ 65% of the Pb is produced in the recycling *s-process*. Truran and Iben (1977) have suggested stars with $M > 15\ M_\odot$ produce many of the *s-process* isotopes in the mass range $25 < A < 70$, that stars with $2\ M_\odot < M < 8\ M_\odot$ make the bulk of the *s-process* isotopes for $A > 70$, and that stars with $M < 1\ M_\odot$ are responsible for ^{206,207,208}Pb and ^{209}Bi. Thus one possible explanation for the HEAO-3 observation of a deficiency of counts in the Pb region is that the nucleosynthetic contribution of stars with $M < 1\ M_\odot$ is under-represented in the cosmic ray source.

With the contribution of the cyclic *s-process* deleted, the modified Solar System source abundances have been propagated through a 7 g cm^{-2} leaky box for comparison with the measured abundances. A detailed look at the contribution of the terminal *s-process* is visible in Figure 2, which compares the abundances of the nuclei above the Te-Ba peak with (solid line) and without (dashed line) the additional material. Calculations show that about 75% of the difference in source abundances appears as contributions to the elements at lower Z. Such is the relative abundance of Pb that this contribution is significant throughout the illustrated charge region. Despite this change, the measured values in the rare-earth region appear too high. This might indicate a more extreme propagation model, but more probable is that the source abundances in the rare-earth region need further adjustment if the data are correct. The rare-earth elements have nearly the same first ionization potentials, all lower than that of iron, but are refractory to differing degrees. Should that have an effect on the injection process (see above), the variation of injection efficiency across these elements migh provide a useful gauge of the nature of preferential acceleration.

5. Conclusions. The most important conclusion of this work is that the overall composition of the galactic cosmic ray source appears remarkably like that of the Solar System. The abundances above

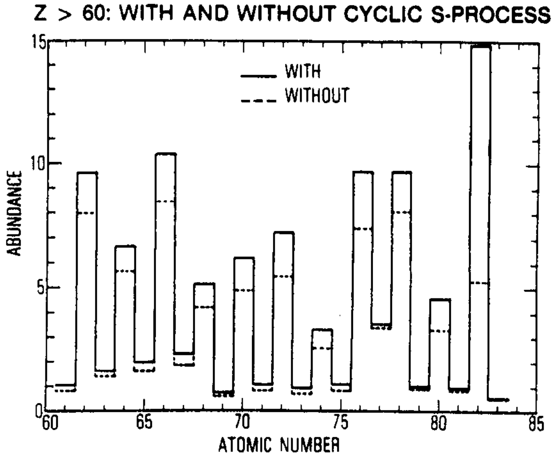

Figure 2. The net contribution to the propagated abundances is illustrated as the difference between the solid line, showing the standard Solar System source, and the dashed line, showing the modified source calculated in this work. Approximately 75% of Pb at the source is incorporated into elements of lower *Z*. The vertical scale is linear, but the units are arbitrary.

Fe display a very Solar-like balance between several different nucleosynthetic processes. However, if the Pb abundance reported by Binns *et al.* (1984) is correct, it might signify the lack of the products of the terminal or cyclic *s-process*. Such evidence could be used to rule out the appearance of stars with masses $M < 1\ M_\odot$ on the roster of cosmic ray sources. Until more precise determinations are available, however, it seems prudent not to consider this abundance as additional confirmation of ever more complex models for selective acceleration.

6. Acknowledgements. The work reported here was supported at Washington University under NASA grant NAG8-448 and McDonnell Center research funds and at the Aerospace Corp. under company-sponsored research funds.

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