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Discrimination between possible cosmic ray sources

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Abstract. Different scenarios of the origin of the cosmic radiation invoke different chemical abundances of the accelerated material. A determination of the abundances of the nuclei in the cosmic rays observed in the solar system can, in principle, be used to discriminate between these different scenarios. Unfortunately, the compositional changes introduced during the propagation of the nuclei through the interstellar medium introduce serious uncertainties in relating the observed composition to that at the source. It is shown here that there are a number of "signature" elemental ratios among the heaviest elements in the cosmic radiation that should allow for clear discrimination between some of the most popular current theories of the origin. These ratios appear to be robust in that they are not strongly energy dependent nor do they depend critically on the precise details of the propagation models or parameters. The proposed HNX mission will be able to determine these ratios with the required accuracy.

Introduction:

Measurements of the abundances of the nuclei in the cosmic radiation observed in the solar system can be used to deduce the abundances at the source, if the corrections for the effects of propagation through the interstellar medium can be adequately modeled. In this paper it is shown that after the application of a relatively simple model of propagation the new data that will be available from forthcoming experiments will make it possible to discriminate between a number of models for the source composition. In particular, it will be possible to distinguish between the effects introduced by a selection bias based on the first ionization potential and one based on the volatility. This will require measurements with sufficient charge resolution to separate the individual elements of the UH nuclei (Z > 28).

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It is generally accepted that the abundances of the elements observed in the cosmic radiation show the effects of a selection mechanism during the acceleration. This selection was originally assumed to depend on the first ionization potential (FIP) of each element. A more recent model suggests instead that the relevant parameter is the volatility (Vol.) which depends on the condensation temperature, T_{cond}. Since there is considerable correlation between FIP and T_{cond} it is not easy to draw a clear distinction between these two scenarios. However, several of the elements heavier than iron, those that makeup the cosmic ray UH nuclei, break this correlation and should allow discrimination. As a example, in what follows the standard cosmic abundances of Anders and Grevasse (1991) have been modified by correction factors, f, based on the values of FIP and T_{cond}. Similar corrections could be applied to different source abundances, such as those if r-process nuclei were dominant in the source. For consistency in this study both selection factors have been based on a “sloped step” model. For FIP a linear interpolation from f = 1.0 to 0.25 has been imposed between 8.5 and 10.0 eV. For

Vol. a similar interpolation is imposed for $T_{cond.}$ between 850 and 1250 K. The resulting factors are shown as a function of elemental charge, Z, in Fig. 1. It can be seen that there are a few elements for which the corrections are significantly different. By measuring the abundances of these elements it should be possible to discriminate between the two scenarios. In practice the most sensitive quantities appear to be the ratios of the abundances of the odd charged elements to their neighboring heavier or lighter even charged elements. These ratios are relatively insensitive to the assumptions of the propagation model, the initial energy at the source or the effects of charge dependent experimental biases.

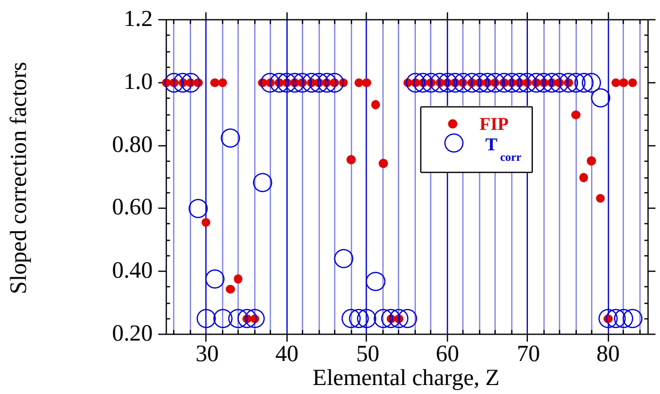

Fig. 1 Correction factors, f, assumed for the selection effects of FIP and Volatility, T_{corr}, as a function of elemental charge.

Sec. 1 UH nuclei propagation: Between $_{28}$Ni and $_{82}$Pb both the source and the propagated cosmic ray abundances decrease by some six orders of magnitude. The propagation of these nuclei has been modeled using a leaky box formalism and cross sections based on the semi-empirical relations of Silberberg and Tsao (1995). These cross sections for the individual isotopes have been corrected for the effects of decay and the stability of some of the K-capture isotopes. A rigidity, R, dependent escape length of the form :

$x_{esc} = 11.3\beta$ g/cm^2 at R < 5 GV, $x_{esc} = 11.3\beta(R/5GV)^{-0.54}$ g/cm^2 at R > 5 GV

where β was the reduced velocity, was assumed, Ptuskin et al, (1999). Ten different initial energies between 1.0 and 10.0 AGeV were assumed at the source and allowance made for the energy losses during propagation. Truncation of the initial pathlength and the effects of reaccelation could be applied if required.

Fig. 2 shows a comparison between the abundances predicted from this program for the cosmic abundances selected by FIP or Vol. This figure shows that the differences between the two predicted cosmic ray distributions are not large. In addition, the experimental difficulties of reliably determining the relative abundances of all these elements over this wide range of charge are challenging. For these reasons it seems clear that rather than trying to determine complete charge spectra it will be far easier to study the relative abundances of elements that are near to each other in the periodic table. Ideally these studies will measure the abundance ratios of neighboring elements, but this requires detectors capable of resolving the generally low abundance odd charged nuclei from the more abundant neighboring even charged nuclei. Such good resolution was not achieved by previous detectors of the UH cosmic ray nuclei, Binns et al. (1989), Fowler et al. (1987), but is expected from the next generation of detectors **(**TIGER, HNX**).**

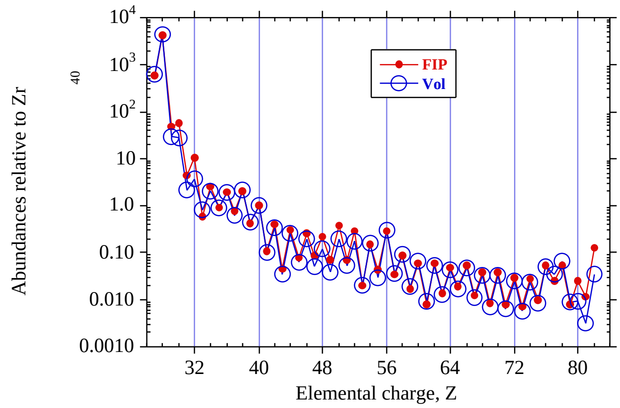

Fig.2 Abundances after propagation for cosmic source corrected for FIP or Vol. Assumes source energy of 5.0 AGeV and minimal truncation of 0.1 g.cm^{-2}.

The abundance ratios of odd to neighboring even elements at the top of the atmosphere can be predicted for various assumed source abundances. Fig. 3 shows the values of the ratios of odd to even charged heavier elements for the two abundance spectra shown in Fig. 2. Several of the more significant ratios that should provide a clear discrimination between the FIP and volatility corrections are indicated on this plot, see Fig. 6. Similarly Fig. 4 shows similar ratios for the cosmic abundances and those assuming a pure r-process both corrected for FIP. Some of the predicted odd-even ratios appear to be particularly sensitive to the assumed source and hence measurement of them should help to define the true source composition.

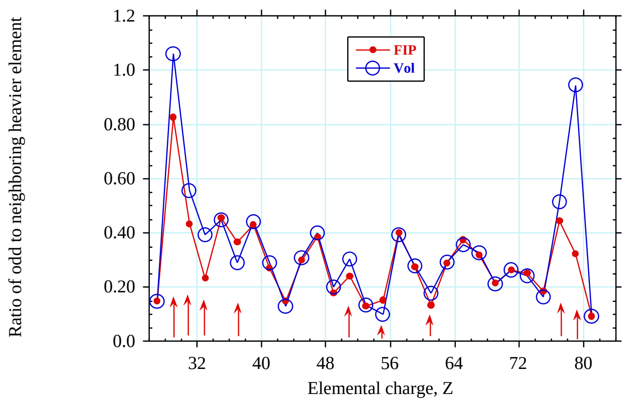

Fig. 3 The ratios between the predicted abundances for FIP and Vol. of each odd charged element and its neighboring heavier even charged element. Discriminating ratios are marked with arrows.

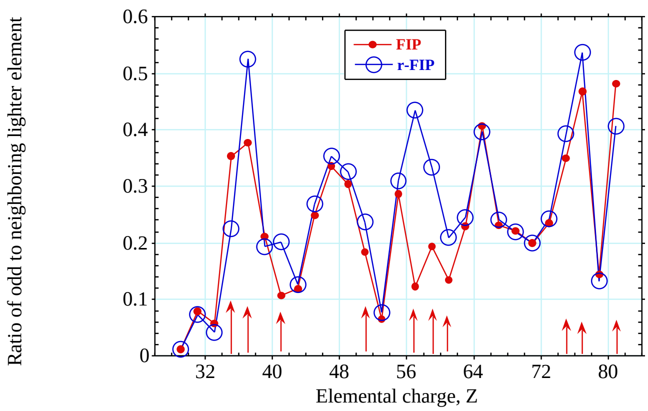

Fig. 4 The ratios between the predicted abundances for cosmic and r-process sources corrected for FIP for each odd element and it neighboring lighter element. Discriminating ratios are marked with arrows

The values of these “signature” ratios are quite robust under variations in the initial assumptions regarding the source energy or the amount of truncation present. For example, Fig. 5 shows, even though the cross sections are energy dependent and the propagation is rigidity dependent, that except at the highest charges, the odd-even ratios are relatively independent of the initial source energy, E_i. Similarly it can be shown that these ratios are not seriously affected by reasonable changes in the assumed values of the amount of truncation or the precise escape length.

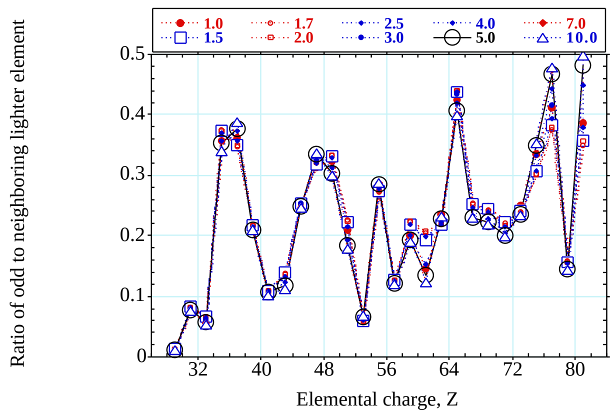

Fig. 5 The odd to neighboring lighter even ratios as a function of energy in AGeV for a FIP corrected cosmic source.

In order to compare the predictions for the two correction factors applied to the cosmic abundances we can consider the differences between these ratios for the two assumptions.

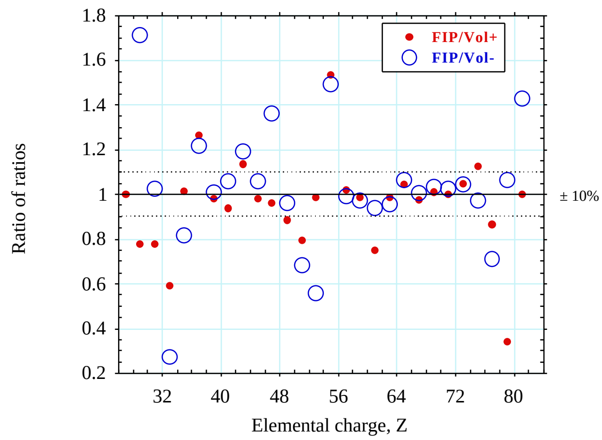

Fig. 6 The ratios of ratios for FIP over Vol for both heavier, +, and lighter, -, neighboring even elements.

Fig. 6 shows the values of the ratios of the individual ratios. It can be seen that in each of the charge regions of most interest, those with $30 \le Z \le 40$, $50 \le Z \le 60$ and $Z > 74$, there are clear values that lie well outside the ± 10% band that probably expresses the statistical limitations of forthcoming experiments.

Sec. 2 Effects of overlying atmosphere. Some of the predicted abundances at the top of the atmosphere have been propagated into the atmosphere, using a slab model and the cross sections based on Bevalac and AGS measurements by Nilsen et al (1995). These results show that the discriminating power of the signature ratios is not seriously degraded when measurements are made from high altitude balloons rather than in space. Fig. 7 shows an example of how the individual odd to even ratios would change in the atmosphere.

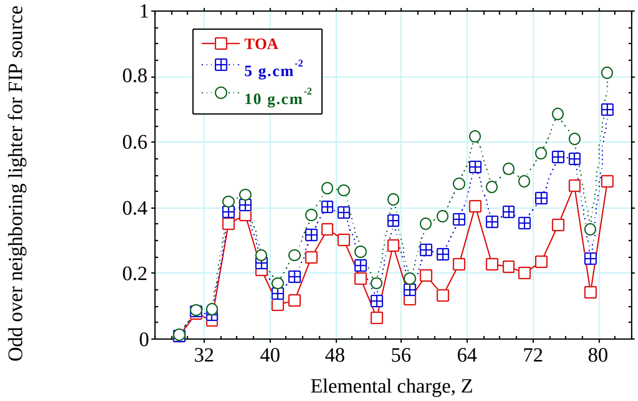

Fig. 7 The ratios of odd to neighboring lighter elements as a function of depth in the atmosphere for a FIP source at 5 AGeV.

Note that it can be seen from these ratios that for the heaviest elements the abundances of the more abundant even charge nuclei are reduced while those of the odd charged nuclei are increased. For the lighter elements most of the abundances are reduced. However, Fig. 8 shows that the discrimination based on the signature ratios of ratios between FIP and Vol sources is not seriously diminished under 5 or even 10 g.cm^2 of overlying atmosphere. It can be seen that the ratios of ratios are hardly changed with increasing depth. Of course the absolute abundances are reduced and the uncertainties due to propagation in the atmosphere are increased as the depth in the atmosphere increases.

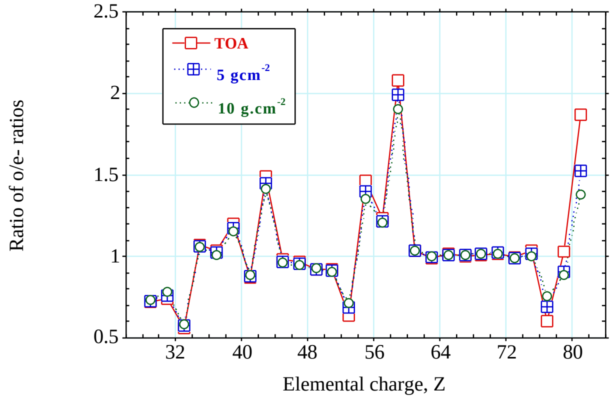

Fig. 8 The variations in the ratios of ratios between FIP and Vol for the odd over the neighboring lighter even elements as a function of depth in the atmosphere.

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