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Propagation of High-Energy Cosmic Rays through the Galaxy: Discussion and Interpretation of TRACER Results

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Abstract: The long-duration balloon flights of TRACER provide new measurements of the intensities and energy spectra of the arriving cosmic-ray nuclei with $5 \leq Z \leq 26$ at high energies. In order to determine the particle composition and energy spectra at the cosmic-ray sources, changes occurring during the interstellar propagation of cosmic rays must be known. We use a simple propagation model with energy-dependent pathlength and derive constraints on the propagation parameters from a self-consistent fit to the measured energy spectra. We use the model to obtain the relative abundances of the cosmic ray nuclei at the acceleration site.

Introduction

The TRACER long-duration balloon flight in 2003 has provided a rather comprehensive data set on the energy spectra of primary cosmic ray nuclei from oxygen to iron (Z = 8 to 26) up to energies around, and for some species above, 10^{14} eV. Where comparisons with previous measurements can be made, satisfying agreement between different data sets exists [1]. The energy spectra reach similar, if not identical, power-law slope towards high energy, and spectral breaks of any kind are not noticeable. This strongly indicates a common origin of these elements. However, in order to determine the spectra and relative abundances at the sources, the mode of galactic propagation must be understood.

Propagation Model

At relativistic energies, the fate of a cosmic-ray nucleus propagating from the acceleration site to the observer is determined by the competing actions of escape from the galaxy by diffusion and by loss due to nuclear interaction in the interstellar medium (ISM). For simplicity, one may characterize these processes by two parameters, the escape pathlength Λ_{esc}, and the interaction pathlength Λ_{int}. In general, Λ_{esc} depends on energy, while Λ_{int} scales with $A^{-2/3}$ (where A = atomic number), i.e., Λ_{int} decreases with increasing nuclear charge Z. The energy dependence of Λ_{esc} is usually derived from the intensity ratio of secondary to primary cosmic rays; here we use the parameterization given by Yanasak et al. [2], where *R* = particle rigidity, and $\beta = v/c$.

$$\Lambda_{esc} = \frac{26.7\beta}{(\beta R)^{0.58} + (\frac{\beta R}{1.4})^{-1.4}} + \Lambda_0 \qquad (1)$$

This is illustrated in Figure 1. We note that the escape pathlength approaches the commonly accepted form $\Lambda(E) \propto E^{-0.6}$ at high energy, but we also notice that at energies around and above 100 GeV/nucleon the observational data provide little constraint on $\Lambda_{esc}(E)$. It is quite possible that Λ_{esc} approaches a non-zero residual value Λ_0 at high energy.

In the simplest form, the relation between the observed energy spectrum $N_i(E)$ of a cosmic ray nucleus and the spectrum at the source $Q_i(E)$ is :

$$N_i(E) \propto \Lambda \cdot (Q_i(E) + \text{spallation term}) \qquad (2)$$

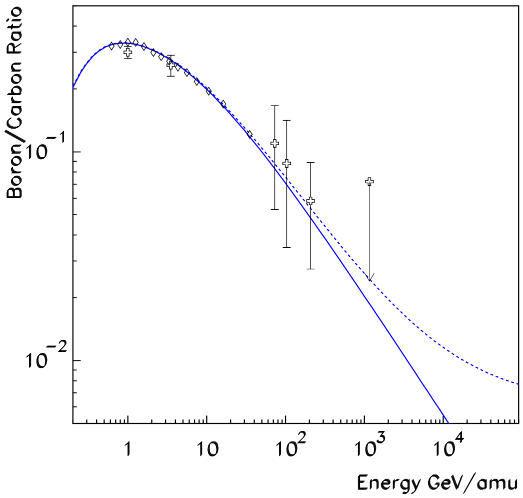

Figure 1: Boron to carbon ratio with data from HEAO-3 and CRN. The solid line represents a parameterization given by Yanasak [2]. The addition of a residual pathlength of Λ_0 = 0.1 g/cm^2 to the Yanasak parametrization is presented by the dashed line.

with

$$\frac{1}{\Lambda} = \frac{1}{\Lambda_{esc}(E)} + \frac{1}{\Lambda_{int}(Z)}, \tag{3}$$

and "spallation term" refers to the production of this species by nuclear spallation in the ISM.

Over certain energy regions, Λ_{esc} and Λ_{int} are commensurate, as shown in Figure 2, and in general, the smaller of the two parameters is the one which dominates in equation 3. We assume that the source energy spectrum is a power law with exponent α, i.e. $Q_i(E) \propto E^{-\alpha}$. A power law exponent not much in excess of $\alpha = 2.0$ would be expected for strong shocks in supernova shock acceleration models. We now compare the observed cosmic-ray spectra (see Figure 1 in Boyle [1]) with the predictions of this simple propagation model. We assume that all species have the same source index α, but we use the value of α and that of the residual pathlength Λ_0 as fit parameters. Figure 3 shows the energy spectra (multiplied with E$^{2.5}$), together with fitted curves corresponding to α = 2.3 and Λ_0 = 0 g/cm^2 (dashdot line) and 0.1 g/cm^2 (solid line). Clearly, the fits shown are quite good, but may not

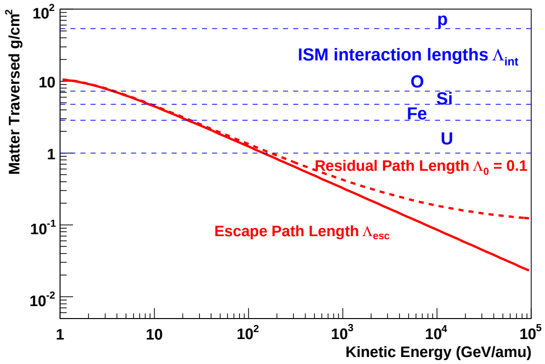

Figure 2: Escape path length (red curve) and interaction path length (dashed lines) versus energy. The interaction pathlengths are given for several elements including, for illustration, protons and uranium.

be unique. A χ^2-test of the spectra of all elements (from oxygen to iron) leads to the contour lines shown in Figure 4. A slight increase in the power-law index from α = 2.2 to 2.4 could be compensated with values of Λ_0 from 0 to 0.5 g/cm^2. However, the larger the value of α, the more difficult it is to accommodate in shock-acceleration scenarios. It is clear that a direct measurement of Λ_{esc} at higher energies and high precision is essential to resolve this issue.

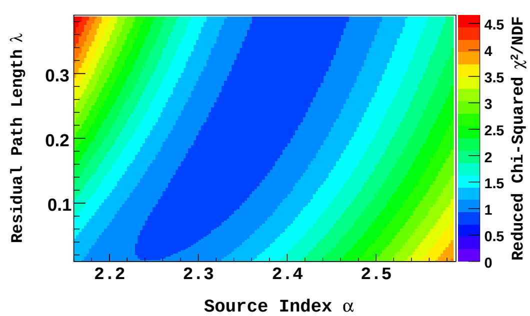

Figure 4: Composite χ^2 for Λ_0 and α for the eight TRACER elements.

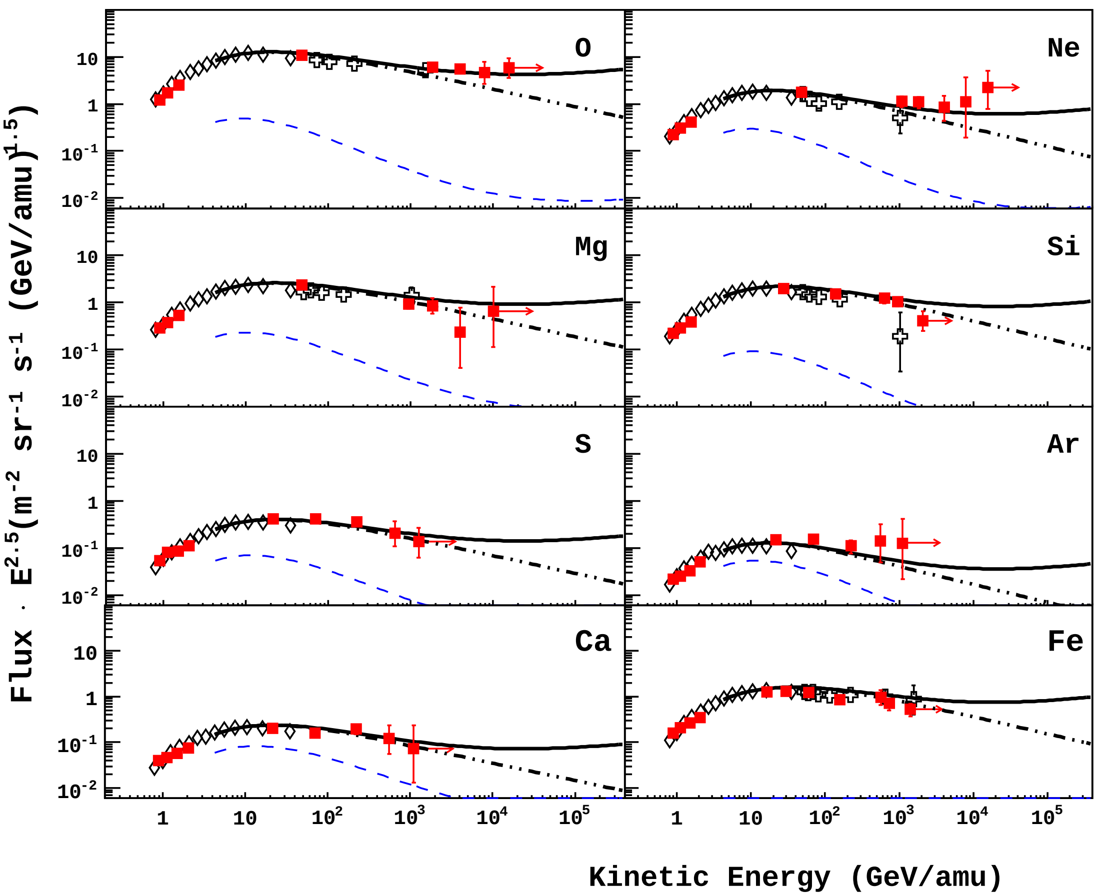

Figure 3: Differential energy spectra, multiplied with $E^{2.5}$, from TRACER (solid squares), HEAO-3 [3] (open diamonds), and CRN [4] (open crosses). The black curves refer to predictions from a simple propagation model (dash-dot line α = 2.3 and Λ_0 = 0 g/cm^2; solid line α = 2.3 and Λ_0 = 0.1 g/cm^2) and the blue dashed line is the contribution of secondary particles. Note the energy scale is in GeV/amu.

Simple Consequences of the Model

We may construct "expected" energy spectra for all nuclei, taking $\alpha = 2.3$ and $\Lambda_0 = 0.1$ g/cm^2, and then generate single power-law fits to these spectra over 20 to 1000 GeV/nucleon. This index would slowly change with energy, as shown in Figure 5. However, the change is not as significant as to be observable in the experimental data. We also may use the propagation model to determine the fraction of secondary, spallation-produced nuclei in each observed spectrum. This is shown in Figure 3 (blue dashed lines), indicating a secondary contribution just in the 1-percent region in most cases.

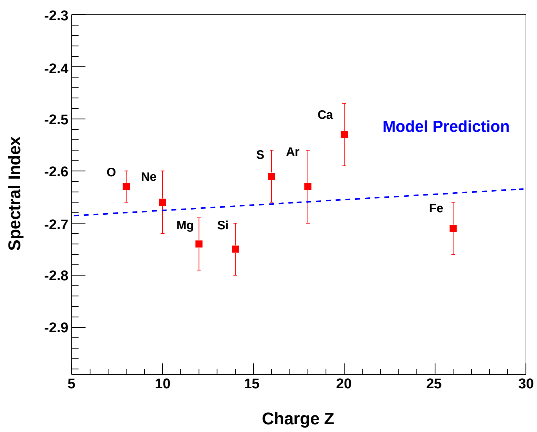

Figure 5: The best fit power law indices from TRACER 2003 as a function of charge Z. The dashed line represents a theoretical evolution of the spectral index using the propagation model detailed in the text.

Finally, we determine the relative abundances of the elements at the cosmic-ray source (Figure 6), and again verify the well-known anti-correlation with the first ionization potential or with volatility.

Conclusion

The TRACER results on the elemental composition of cosmic ray nuclei lead to a number of details that characterize the source of high-energy cosmic rays. In general, they provide support for a shock acceleration mechanism in supernova remnants, and for a common origin of all species. As the measurements extend into the $10^{14} - 10^{15}$ eV

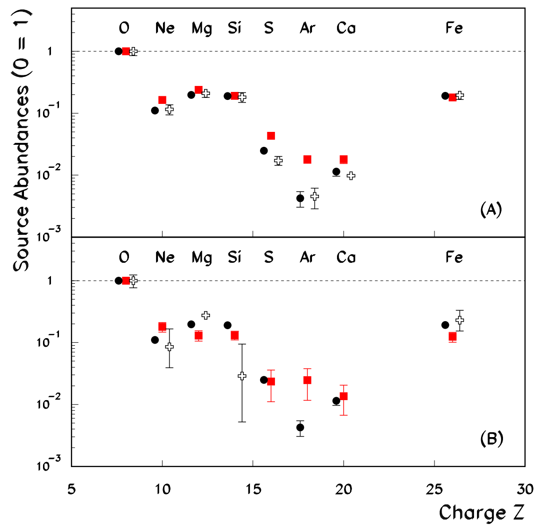

Figure 6: Galactic cosmic ray source abundances from TRACER (red squares) and CRN (crosses) normalized to oxygen and compared to the HEAO-3 results at 1-30 GeV/n (circles). **(A)** CRN at 100 GeV/n and TRACER at 10-250 GeV/n **(B)** CRN at 1000 GeV/n and TRACER $>$ 250 GeV/n. Note that the charge Z is offset for each element for clarity.

region, it is noteworthy that there does not seem to be an indication for any irregular behavior of any of the spectra. The most important task for new measurements appears to be an extension of the secondary-primary intensity ratio to higher energies. We expect that the TRACER results from its 2006 flight, which are currently being analyzed, will lead to new results in this area.

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