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Primary and secondary contributions to arriving abundances of cosmic-ray nuclides

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Abstract: The arriving abundances of a variety of cosmic-ray nuclides consist of comparable amounts of primary material produced by stellar nucleosynthesis and secondary matter resulting from fragmentation of heavier nuclei by collisions during interstellar propagation. We discuss a technique for extracting the primary and secondary contributions that takes advantage of energy spectra of individual nuclides available from the Advanced Composition Explorer mission, a data base of measured and calculated fragmentation cross sections, and the leaky box model of interstellar propagation.

Introduction

As a result of measurements of the elemental and isotopic composition of galactic cosmic rays arriving near Earth in the energy range ~ 50 to ~ 500 MeV/nuc by NASA's Advanced Composition Explorer (ACE [1]), abundances of essentially all stable and long-lived nuclides up to $Z = 30$ are now known with reasonable precision.

The determination of the relative contributions of primary and secondary cosmic rays to the abundances of individual nuclides measured near Earth is essential for a variety of investigations. The primary components are the starting point for studies of source composition and of the galactic origins of the material accelerated to cosmic-ray energies. The secondaries, on the other hand, provide observational constraints needed for the development of models of interstellar propagation. The arriving abundances of a limited number of nuclides consist so overwhelmingly of either primaries (e.g., ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{56}Fe) or secondaries (e.g., Li, Be, B, Sc) that no calculation of the relative contributions of these two populations is needed to carry out the investigations. For most nuclides, however, a careful analysis is needed in order to decompose the observed abundances into their component parts.

This analysis involves calculating the effects of interstellar propagation and solar modulation to determine how the primary composition at the cosmic-ray sources is transformed into the mixed composition that we measure. Because these calculations involve numerous parameters, and in particular a wide variety of fragmentation cross sections, the associated uncertainties can be difficult to assess. In this paper we discuss an approach to deriving the primary and secondary fractions in the arriving cosmic rays in a way that seeks 1) to maximize the use of observational constraints, 2) to minimize the number of parameters that must be known, and 3) to explicitly display the dependence on the key parameters of the propagation calculation and thereby facilitate the evaluation of associated uncertainties. Our approach is an extension of the "secondary tracer" technique [2].

Energy Spectra

Figure 1 shows examples of solar-minimum energy spectra for selected nuclides measured using the

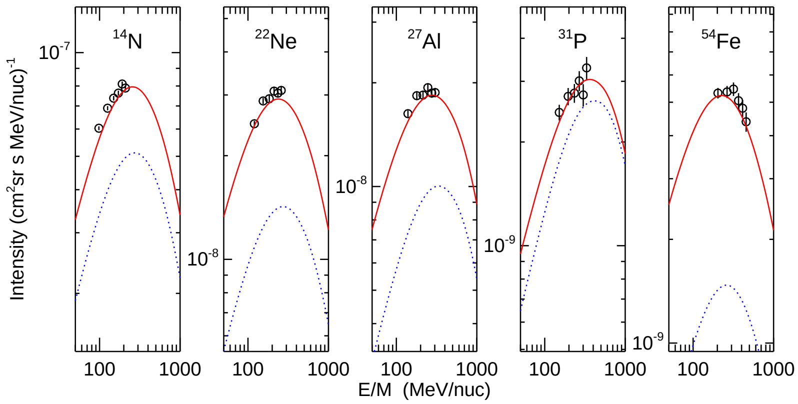

Figure 1: Comparison of measured spectral points (circles) with calculated spectra at 1 AU (solid curves) and secondary contributions to the calculated spectra (dotted curves). Note that the the vertical scales differ from panel to panel, although in each case they cover one order of magnitude in intensity.

Cosmic Ray Isotope Spectrometer (CRIS [3]) on ACE. In most cases the statistical accuracy of the measurements is sufficient to determine the shape of the spectra, in addition to the overall intensity.

The leaky box model (e.g., [4]) can be used to relate the source spectrum of a cosmic-ray nuclide i (denoted by q_i) to the equilibrium interstellar spectra of that nuclide (φ_i) and of heavier nuclides (φ_j) that can produce it by nuclear fragmentation:

$$q_i = \frac{\varphi_i}{\Lambda_{\rm esc}} + \frac{\varphi_i}{\Lambda_i} - \sum_j \frac{\varphi_j}{\Lambda_{ji}} - \frac{\partial}{\partial \epsilon}\left(w_i \varphi_i\right). \quad (1)$$

Here Λ_i and Λ_{ji}, the mean free paths for collisions that destroy nuclide i or produce it from nuclide j, are inversely proportional to the reaction cross sections. The quantity $w_i \equiv d\epsilon/dx$, the rate of loss of energy per nucleon (ϵ) per g/cm^2 of interstellar matter traversed, appears in the term describing spectral changes due to ionization energy loss.

In the first term on the right hand side of Eq. 1, $\Lambda_{\rm esc}$ is an empirical mean free path for cosmic rays to escape from the galactic confinement volume. We have adopted the energy dependence of $\Lambda_{\rm esc}$ found by [5], $\Lambda_{\rm esc} = \Lambda_0\, \beta/((\beta\, R/1\;{\rm GV})^{0.6} + (\beta\, R/1.3\;{\rm GV})^{-2.0})$, where β is the particle velocity in units of the speed of light, R is magnetic rigidity, and Λ_0 is a constant that we adjust to optimize the consistency between the calculated and observed abundances of a number of nuclides that are expected to be dominantly secondary.

It is notable that in the leaky box model the source spectrum can be expressed explicitly in terms of equilibrium interstellar spectra and quantities that can be measured in the laboratory. The only impediment to going directly from cosmic ray measurements to source abundances is the fact that the spectra measured near Earth have been modified by the effects of solar modulation. However, a relatively simple solar modulation model including the effects of diffusion, convection, and adiabatic deceleration, can account reasonably well for the shapes of measured cosmic-ray spectra [6, 7]. This can be seen in Fig. 1 where the near-Earth spectra obtained from a leaky-box propagation calculation followed by a solar modulation calculation (solid curves) exhibit shapes similar to those seen in the ACE/CRIS measurements.

Thus we can obtain estimates of the equilibrium interstellar spectra, φ_i, as follows. First we assume a nominal set of source abundances and a simple source spectral shape that agrees with measured spectra at high energies. A propagation calculation based on Eq. 1 provides predictions of the equilibrium interstellar spectra. Applying the solar modulation model then yields the corresponding spectra near Earth, J_i, which can be compared with cosmic ray intensity measurements as illustrated in Fig. 1. As seen in this figure, the calculated spectral shapes agree rather well with the measurements but there can be discrepancies in the overall intensities. These could arise, for example, due to inaccuracies in the initially assumed source abundances or in the cross sections that are used. For each nuclide we calculate an energy-independent factor by which we can multiply its calculated near-Earth spectrum to provide the best agreement with the observations. Using the same factor to scale the calculated equilibrium interstellar spectrum should give a reasonably good estimate of the true interstellar spectrum, except possibly at energies so low that solar modulation prevents the particles from reaching the inner heliosphere.

These scaled interstellar spectra, which we denote by φ'_j, can then be used in the secondary production sum in the third term on the right of Eq. 1. The use of these parent nuclei interstellar spectra that are constrained by the measurements provides an important advantage: the calculation of the secondary contribution to φ_i no longer requires a knowledge of any fragmentation cross sections except those *directly* involved in the production and destruction of nuclide i.

Having included these improved secondary production yields one can derive improved source abundances that could, if necessary, be used as the starting point for another iteration of this calculation. In practice, however, an iterative calculation is not needed because the originally assumed source abundances are only used for deriving the *shapes* of the equilibrium spectra.

Secondary Contributions

The energy spectrum of secondaries that contribute to the observed spectrum of a given cosmic-ray nuclide can be simply calculated by setting $q_i = 0$ in Eq. 1 and calculating φ_i^s ("s" denoting secondary) that satisfies the equation with this zero source abundance. In this calculation one uses the same equilibrium interstellar spectra for the parent nuclides previously derived ($\varphi_j = \varphi'_j$). The dotted curves in Fig. 1 show examples of secondary contributions calculated in this way.

Following this procedure we have calculated the secondary fraction of each nuclide as $f_i^s \equiv J_i^s/J_i$, where the J's are the near-Earth spectra obtained by modulating the corresponding φ's. In Fig. 2 we show the secondary fractions evaluated at 200 MeV/nuc, an energy in or near the range of the ACE/CRIS measurements for all of the nuclides shown. Purely secondary nuclides should appear with an ordinate ~ 1 on this plot. In fact, Λ_0, the overall normalization of $\Lambda_{\rm esc}$, has been adjusted in an attempt to maximize the number of dominantly-secondary nuclides that yield $f^s \simeq 1$. It is possible for calculated secondary fractions to come out $>$1 if a cross section important for the production of a nuclide is overestimated so that the calculated secondary production exceeds the total measured abundance of that nuclide.

To examine the sensitivity of the secondary fraction results to the value of Λ_0 we have repeated the calculation of the secondary fraction using values of this parameter ranging from 10 to 40 g/cm^2 in steps of 5 g/cm^2. In Fig. 2 circles are used to plot the result obtained using the nominal $\Lambda_0 = 25$ g/cm^2 while the other values are indicated by horizontal ticks along a vertical bar through this point (with secondary fractions increasing with increasing Λ_0). As expected, there is a strong dependence of f^s on Λ_0 for dominantly-secondary nuclides. This dependence is weaker for the higher-mass secondaries because for these species escape plays a less important role relative to fragmentation in determining the amount of interstellar matter traversed.

For dominantly-primary nuclides the inferred secondary fractions are very insensitive to the assumed value of Λ_0. However this does not necessarily mean that derived source abundance ratios will have this same insensitivity. Going from the primary component of a given nuclide arriving near Earth to the source abundance of that nuclide depends on the overall mean free path for fragmentation plus escape losses, as can be seen by considering Eq. 1 including only the first two of the terms on the right hand side. Source abundance ratios between two nuclides (i=1 and 2) having significantly different masses can still be sensitive to Λ_0 because $\Lambda_{\rm esc}$ will not cancel out in the ratio of overall loss lengths, $\left(\Lambda_{\rm esc}^{-1} + \Lambda_1^{-1}\right) / \left(\Lambda_{\rm esc}^{-1} + \Lambda_2^{-1}\right)$. When the masses of the two nuclides being compared are similar this correction tends to be less important.

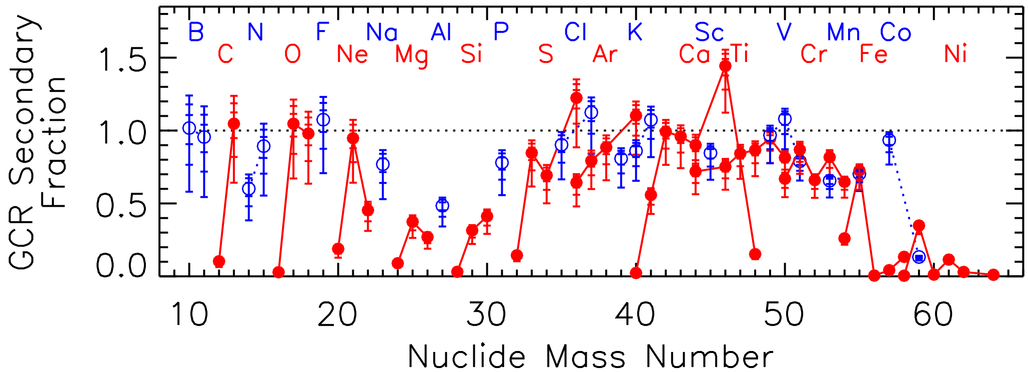

Figure 2: Derived secondary fractions in the arriving cosmic rays for isotopes of the elements in the range $5 \leq Z \leq 28$ inferred from the ACE/CRIS measurements are shown as a function of mass number. Values for even-Z (odd-Z) elements are shown as filled (open) points with solid (dotted) lines connecting points corresponding to isotopes of the same element.

Cross Section Uncertainties

When the equilibrium interstellar spectra of the parent nuclides are replaced with the values derived by scaling from the observed spectra ($\varphi_j = \varphi'_j$), the expression given for q_i in Eq. 1 also lends itself to a simple propagation of errors calculation that can be used to assess the sensitivity of the derived source abundances to the production cross sections ($\propto \Lambda_{ji}^{-1}$) and to the destruction cross sections ($\propto \Lambda_i^{-1}$). This procedure has been used [8] to assess the contribution of production cross section errors to the uncertainties in inferred source abundances of a number of nuclides, assuming a 25% uncertainty in the secondary production sum, $\sum_j \varphi_j/\Lambda_{ji}$. As expected based on the size of the secondary corrections that are required (Fig. 2), large uncertainties were found for the source abundances of Na and P and, to a lesser extent, for ^{14}N and ^{36}Ar. Given the recent progress in the measurement and semiempirical calculation of fragmentation cross sections ([9] and references therein, [10]), more accurate evaluations of the contributions of cross section errors to uncertainties in derived source abundances are now possible.

Additional analysis is needed to assess the uncertainties associated with the energy dependences of the q_i and Λ_{esc}. The latter can have some effect on how well light (LiBeB) and heavy (sub-Fe) secondaries can simultaneously be fit [5]. As can be seen from Fig. 1, some adjustment of the model to improve the agreement with the sub-Fe secondaries is also needed. In some previous studies [11] this has been accomplished by using cosmic-ray pathlength distributions more elaborate than the simple exponential implicit in the leaky-box forumlation.

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