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Mass fractionation in solar energetic particles and the isotopic composition of the corona

R. A. Leske[1], R. A. Mewaldt[1], C. M. S. Cohen[1], E. R. Christian[2], A. C. Cummings[1], P. L. Slocum[3], E. C. Stone[1], T. T. von Rosenvinge[2], and M. E. Wiedenbeck[3]

[1]California Institute of Technology, Pasadena, CA 91125 USA
[2]NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771 USA
[3]Jet Propulsion Laboratory, Pasadena, CA 91109 USA

Abstract. Using the Solar Isotope Spectrometer on the Advanced Composition Explorer, the isotopic composition of solar energetic particles (SEPs) has been measured in 18 large SEP events for abundant elements from C through Ni at energies of tens of MeV/nucleon. Although SEP isotopic composition is found to vary widely from event to event, it is strongly correlated with the elemental composition, suggesting that elemental and isotopic fractionation relative to the coronal source are largely governed by the same processes. Using empirical correlations to correct for the fractionation yields preliminary coronal isotopic abundance values in good agreement with those found in the solar wind, with comparable accuracy.

1 Introduction

One of the goals of the Advanced Composition Explorer (ACE) mission is to determine the isotopic composition of the Sun. Solar energetic particles (SEPs) provide a sample of solar material that may be used for this purpose, but particle acceleration and transport can affect their arriving composition. Two distinct types of SEP events, impulsive and gradual, are usually recognized (Reames, 1995a). In gradual events, particles are thought to originate as solar wind or coronal material accelerated by large shocks driven by coronal mass ejections. Elemental abundances in gradual events are highly variable from event to event but are correlated with the ionic charge to mass ratio, Q/M (Breneman and Stone, 1985). After correcting for this fractionation (Breneman and Stone, 1985; Garrard and Stone, 1993) or averaging over many events (Reames, 1995b), SEP abundances reveal the coronal elemental composition. In principle, the coronal isotopic composition can be similarly obtained from SEPs (Mewaldt and Stone, 1989; Williams et al., 1998).

Prior to ACE there were only a few SEP heavy isotope measurements, and only for elements up to Si (see, e.g. Williams et al., 1998, and references therein). Recent studies using the Solar Isotope Spectrometer (SIS) on ACE have extended SEP isotope measurements to abundant elements through Ni in as many as 18 individual SEP events. Large abundance enhancements and event-to-event variability have been found in these SEP isotopic abundance ratios (see, e.g. Leske et al., 2001a, and references therein). In this report, we summarize the isotopic composition measurements, and using the abundance correlations between different species we empirically correct for the variability and obtain preliminary coronal isotopic abundances from SEPs. More details of the analysis can be found in the full report of this work by Leske et al. (2001a).

Correspondence to: R. A. Leske (ral@srl.caltech.edu)

2 Observations and Analysis

The SIS instrument measures the nuclear charge, Z, mass, M, and total kinetic energy, E, for particles with energies of $\sim$10 to $\sim$100 MeV/nucleon using the dE/dx versus residual energy technique in a pair of silicon solid-state detector telescopes (Stone et al., 1998). For this study, SEP events with high fluxes of heavy ions at $E \gtrsim 15$ MeV/nucleon, where mass resolution is best, were examined. Time profiles of the 18 selected events are shown in Fig. 1, and the time periods used in this study are indicated. Because mass resolution in SIS degraded during the high rate of chance coincidences at the peaks of the two largest events, we restricted the isotopic analysis to the decay phases of these two events. Mass resolution varies with Z and E; for the species and energies studied here it typically ranges from $\sim$0.15 to $\sim$0.3 amu. The analysis required to obtain isotope abundance ratios with this good mass resolution is straightforward; further details including examples of mass histograms are given elsewhere (Leske et al., 1999a,b).

Obtaining coronal abundances from these data is complicated by the fact that the SEP isotopic abundances may vary significantly from event to event (Leske et al., 1999b), as shown for the ^{22}Ne/^{20}Ne ratio in Fig. 2. Surprisingly, it

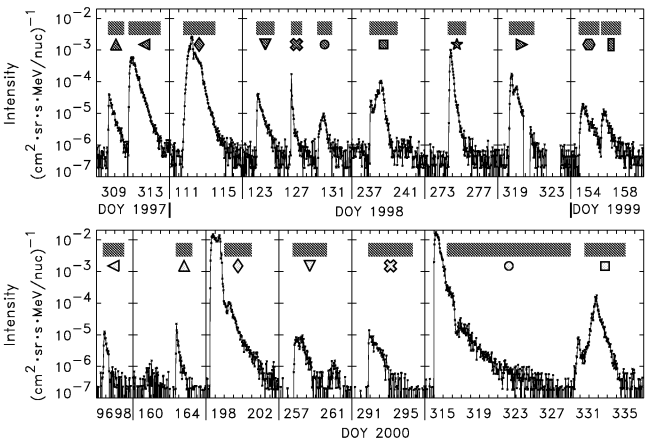

Fig. 1. Time profiles of the 18 SEP events examined here, using hourly-averaged intensities of 21-64 MeV/nucleon oxygen from SIS on ACE. Shaded bars indicate time periods used for the isotope analysis; symbols represent these periods in Figs. 3 and 4.

appears that the composition variability was greatly reduced and nearly absent in the 1999–2000 time frame compared to that seen in 1997–1998. Studies of future events may help to determine whether this is merely a statistical aberration or an unexplained feature of the solar cycle.

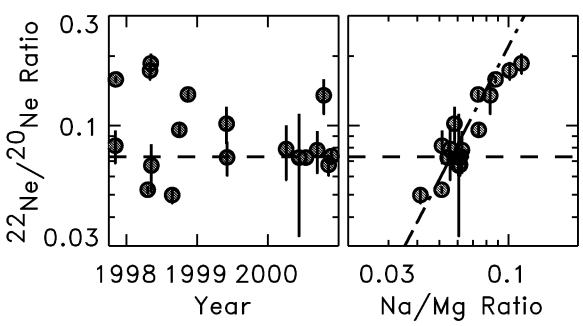

Fig. 2. The SEP ^{22}Ne/^{20}Ne ratio measured by ACE/SIS at $E >$ 15 MeV/nucleon plotted versus the date of the event (left) and the Na/Mg ratio (right). The diagonal line in the right panel shows the correlation expected from Eq. (1), while the horizontal line is the solar wind value (Geiss et al., 1972).

To obtain coronal abundances from the highly variable SEP isotope measurements, we make use of the experience gained in studying elemental abundances. The variations of heavy ion elemental abundances in individual gradual events have been found to scale reasonably well as a power law in the ionic charge to mass ratio, Q/M, with a different power law index for each SEP event (Breneman and Stone, 1985). Since Q/M will differ for two isotopes of the same element through the mass number, this same mechanism should produce variations in the isotopic enhancements, and there should be a predictable correlation between elemental and isotopic abundances. Following Mewaldt and Stone (1989), if we base the power law fractionation index on the abundance ratio of any two reference species, such as Fe/O, Na/Mg, or, in general terms, R_1/R_2, it readily follows (using $x^{\ln y} = y^{\ln x}$) that the enhancement or depletion of the SEP abundance ratio for isotopes a and b of element X would be:

$$\frac{({}^{a}\mathrm{X}/{}^{b}\mathrm{X})_{\mathrm{SEP}}}{({}^{a}\mathrm{X}/{}^{b}\mathrm{X})_{\mathrm{corona}}} = \left(\frac{(\mathrm{R}_1/\mathrm{R}_2)_{\mathrm{SEP}}}{(\mathrm{R}_1/\mathrm{R}_2)_{\mathrm{corona}}}\right)^{\frac{\ln(b/a)}{\ln[(Q/M)_{\mathrm{R}_1}/(Q/M)_{\mathrm{R}_2}]}} \quad (1)$$

since Q should be the same for two isotopes of the same element.

A reasonable correlation has been shown between isotopic abundances and the Fe/O ratio (Leske et al., 1999a,b) but uncertainties in the value of Q(Fe), which is not often measured at SIS energies (see, e.g. Leske et al., 2001b, and references therein), make it difficult to evaluate Eq. (1) and directly compare the correlation with predictions. In addition, in gradual SEP events the abundances of elements with low first ionization potential (FIP), such as Fe, are generally enhanced over those with high FIP, such as O, by an amount which also varies from event to event (Garrard and Stone, 1994; Mewaldt et al., 2000). This FIP-fractionation variability can affect elemental but not isotopic ratios, blurring the expected correlation.

With the appropriate choice of reference species, such as Na/Mg, the isotopic and elemental abundances are indeed correlated approximately as expected from Eq. (1), as shown in Fig. 2. Both Na and Mg are low-FIP elements, so this ratio is unaffected by variable FIP fractionation. As pointed out by Cohen et al. (1999), ions of both elements are theoretically expected to have ∼2 electrons attached over a broad range of coronal temperatures (Arnaud and Rothenflug, 1985), and since ^{23}Na is neutron-rich with respect to ^{24}Mg, there is a significant difference in Q/M. The diagonal line in Fig. 2 shows the correlation expected from Eq. (1), assuming Q(Na)=9 and Q(Mg)=10. While this very simple model provides a good first order fit to the data, the actual correlation appears to be shallower than expected.

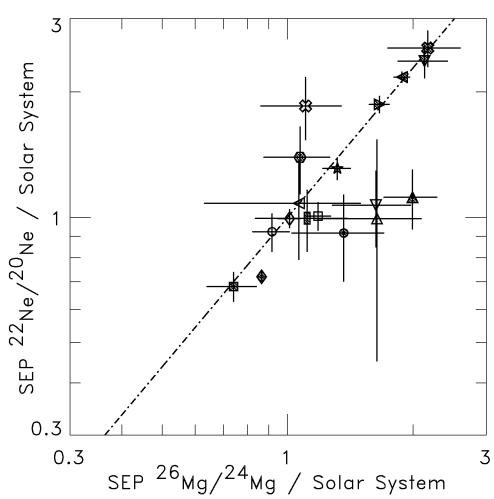

Fig. 3. The ^{22}Ne/^{20}Ne versus ^{26}Mg/^{24}Mg isotopic ratios in each of the SEP events shown in Fig. 1, normalized to standard solar system values (Anders and Grevesse, 1989). The diagonal line shows the correlation expected using Eq. (1).

As discussed by Leske et al. (2001a), the discrepancy be-

tween the data and the expected correlation in Fig. 2 may be due to the fact that the predicted correlation is very sensitive to Q, and it is unlikely that Q(Na) is exactly 9 and Q(Mg) is exactly 10 in every event as assumed. If Q is the same for 2 isotopes of the same element, then using an isotope ratio as the reference value should yield a better correlation.

The correlation between the ^{22}Ne/^{20}Ne and ^{26}Mg/^{24}Mg ratios illustrated in Fig. 3 agrees very well with expectations for most of the events with the better-determined values; at least no systematic deviation from the expected trend is evident. The outliers are smaller events with large uncertainties and most are not seriously discrepant statistically, but it is interesting to note that they tend to lie near a value of unity on one of the two axes, as if only one isotope ratio is fractionated while the other is unaffected. Since these outlying events are among the smallest in our study, even a small amount of contamination from impulsive events might significantly alter their composition. The mechanism responsible for the ^{3}He enrichment of impulsive events might also selectively enhance other species with discrete values of Q/M at higher harmonics of the ^{3}He cyclotron frequency (Mason et al., 1980), and in fact significant enrichments of both ^{22}Ne and ^{26}Mg have been reported in ^{3}He-rich periods (Mason et al., 1994; Slocum et al., 2001). If it were possible for the resonance to affect a narrow enough frequency range, perhaps only one of these two species might be enhanced, resulting in a pattern such as appears to be present in Fig. 3.

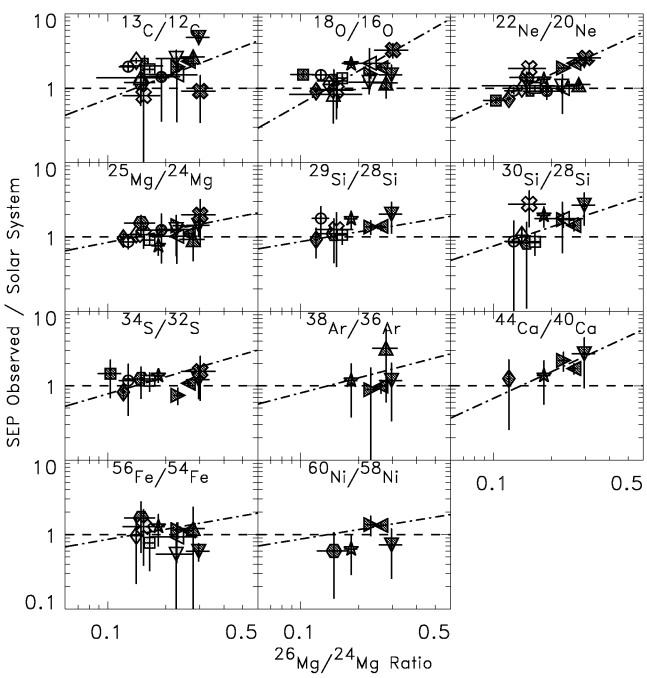

Fig. 4. Eleven SEP isotope abundance ratios normalized to standard abundances (Anders and Grevesse, 1989) plotted versus the ^{26}Mg/^{24}Mg ratio. Symbols indicate the SEP events shown in Fig. 1. Diagonal lines show expected correlations using Eq. (1).

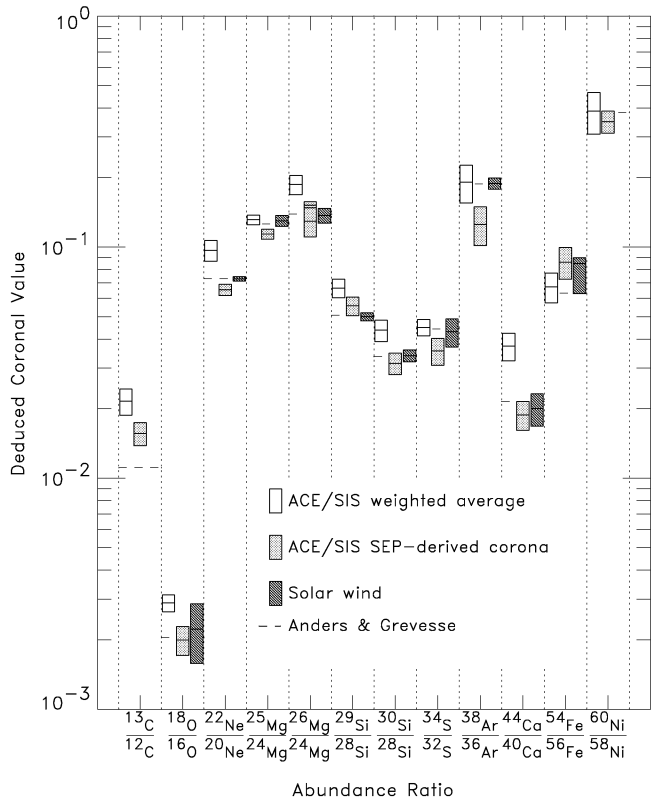

Fig. 5. Deduced coronal source isotopic abundance ratio averages from SIS SEP measurements without correcting for fractionation (open boxes) and after correction (light grey boxes) by Eq. (1). For comparison, standard solar system values (dashed lines; Anders and Grevesse (1989)) and measured solar wind values (dark grey boxes; see Wimmer-Schweingruber et al. (1999) and references therein) are shown. The ^{26}Mg/^{24}Mg ratio was used as the fractionation correction reference value for everything other than the ^{26}Mg/^{24}Mg ratio, for which Na/Mg was used.

3 Results

Of the 2 isotopic ratios in Fig. 3, we chose ^{26}Mg/^{24}Mg as our abundance standard so that we can obtain the SEP Ne composition in this study, which is of interest since the composition of Ne differs in various solar system materials. The SEP abundance values for 11 isotope ratios for elements from C to Ni are shown plotted versus this reference ratio in Fig. 4. The data seem to follow the expected trends for species such as Ne, Mg, Si, and Ca. For many of the heavy elements from S and above, the agreement between the more limited data and the expectations may break down, which might indicate the actual dependence on Q/M is not a simple power law for all Q/M as we assumed. For ^{13}C, 12 of the 15 data points fall above the expected correlation, including most of those for which the ^{26}Mg/^{24}Mg and other ratios show little or no fractionation. This preliminary result suggests that ^{13}C is routinely enhanced or ^{12}C is depleted in SEP events relative to terrestrial abundances. We hope to extend the isotope measurements to include ^{15}N to see if it is similarly affected.

Preliminary results obtained by solving Eq. (1) for the

coronal isotope ratios and averaging over all the SIS measurements are shown in Fig. 5. For comparison, we have also calculated the weighted average without correcting for the fractionation. This may be more appropriate for cases such as S or Fe where the data may not follow the expected fractionation correlations in Fig. 4, and with a large enough data set (if unbiased by selection effects) may even average out to the coronal value as seems to be the case for elemental abundances (Reames, 1995b). Also, the uncorrected average represents the average arriving solar particle composition at 1 AU, and in the case of ^{22}Ne/^{20}Ne, we find the uncorrected ratio consistent with the value of $\sim$0.09 of the so-called SEP component implanted in lunar soils (Wieler, 1998). Both corrected and uncorrected SEP values are compared with standard solar system values (Anders and Grevesse, 1989) and existing solar wind values (Wimmer-Schweingruber et al., 1999) in Fig. 5.

It is encouraging that this preliminary attempt to obtain coronal abundances from the fractionated SEPs seems to yield reasonable values. Except for ^{13}C, all of the isotope abundances are within 2.5σ of the Anders and Grevesse (1989) "solar system" values. Although the corrected ^{22}Ne and ^{38}Ar are low compared to Anders and Grevesse, for both these species Anders and Grevesse adopted the solar wind values as their standard without accounting for mass fractionation in the solar wind of perhaps several percent (Kallenbach et al., 1998). So far, Ni isotope abundances have not been reported from solar wind data, so the SEP value given here is the first determination of the coronal ^{60}Ni/^{58}Ni ratio.

In many cases the uncertainties on the SEP-derived coronal isotope values are comparable to those obtained from solar wind measurements. Additional SEP events such as those of March and April 2001 should help reduce the uncertainties for species such as Ar to Ni where there are still only a few measurements, but for most of the others a better theoretical understanding of the mass fractionation process is needed to make much further progress. Ongoing measurements of the apparent decreasing variability in recent events (Fig. 2), the possible fractionation of only some isotope ratios (Fig. 3), and the frequent enhancement of ^{13}C (Fig. 4) may help to shed light on the nature of the fractionation process.

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