Measurements of the Heavy–Ion Isotopic Composition of Solar Energetic Particles

R. A. Leske[1], R. A. Mewaldt[1], E. R. Christian[2], C. M. S. Cohen[1], 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, Greenbelt, MD 20771 USA*
[3]*Jet Propulsion Laboratory, Pasadena, CA 91109 USA*

Abstract

Using the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE) spacecraft, we have measured the isotopic composition of ten elements from C to Ni ($Z = 6$ to 28) at energies of tens of MeV/nucleon in as many as nine solar energetic particle (SEP) events that have occurred since November 1997. We find that the isotopic composition varies dramatically from event to event. For example, the ^{22}Ne/^{20}Ne ratio ranges from ~ 0.7 to 2 times the solar wind value. The mass fractionation is strongly correlated with the Fe/O and other element abundance ratios, suggesting that the elemental and isotopic fractionation are governed by the same process.

1 Introduction:

Solar energetic particles (SEPs) can be used to study the composition of the solar atmosphere, as well as particle acceleration and transport processes which may alter their composition. Elemental abundances in large, gradual SEP events are known to vary from event to event. These variations are found to be correlated with the ionic charge to mass ratio, Q/M (Breneman & Stone, 1985). When corrected for this fractionation, SEP abundances can be used to determine the elemental composition of the corona (Breneman & Stone, 1985; Garrard & Stone, 1993; Reames 1995) independently of spectroscopic measurements. In principle, the isotopic composition of the corona can also be deduced from SEP studies (Mewaldt & Stone, 1989; Williams et al., 1998), which has not been possible spectroscopically for most isotopes.

Earlier SEP isotope measurements (e.g., Dietrich & Simpson, 1979; Mewaldt et al., 1984; Simpson et al., 1983; Williams et al., 1998) have been limited by collecting power and mass resolution to elements up to Si. The isotope values that were measured usually appeared to be consistent with terrestrial abundances within large uncertainties. Isolated differences were occasionally found for gradual events (Mewaldt & Stone, 1989; Williams et al., 1998), and there were indications of significant enrichments of ^{22}Ne in ^{3}He-rich periods (Mason et al., 1994).

In new studies by the Advanced Composition Explorer (ACE), large enhancements were found in the 6 November 1997 SEP event for many heavy isotopes from ^{13}C to ^{60}Ni, with the ^{22}Ne/^{20}Ne ratio enhanced by a factor of 2.08 ± 0.09 over the solar wind value (Leske et al., 1999a). Measurements of the ^{22}Ne/^{20}Ne abundance ratio in 9 SEP events observed at energies of $24 - 72$ MeV/nucleon by the Solar Isotope Spectrometer (SIS) on ACE (Leske et al., 1999b) demonstrated that this abundance varies widely from event to event. In this present report, we show that abundances of other heavy ions from C to Ni also vary greatly from event to event and that this mass fractionation is correlated with the previously known elemental fractionation. A companion paper by Mewaldt et al. (1999) further discusses the implications of these measurements.

2 Data Analysis:

The SIS instrument consists of a pair of silicon solid-state detector telescopes with a combined geometry factor of 38 cm^{2}sr (Stone et al., 1998). The nuclear charge, Z, mass, M, and total kinetic energy, E, can be determined for particles with energies of ~ 10 to ~ 100 MeV/nucleon using the dE/dx versus residual energy technique, with a mass resolution of ~ 0.15 to > 0.3 amu, depending on E and Z.

As an example of the species observed and the resolution of SIS, mass histograms of 10 elements during the 14 November 1998 SEP event are shown in Figure 1. Multiple determinations of Z and M were required to be consistent with each other in order to reject events that underwent nuclear interactions in the instrument or involved chance coincidences. The measured trajectory of each particle was also used to reject those particles which could have exited through the sides of the instrument without stopping. More analysis is required to determine abundances for relatively rare isotopes, such as ^{15}N, ^{17}O, ^{21}Ne, and ^{33}S, which may have large contributions from tails of much more abundant neighboring isotopes. Most isotopes are well resolved, however, with good statistical accuracy.

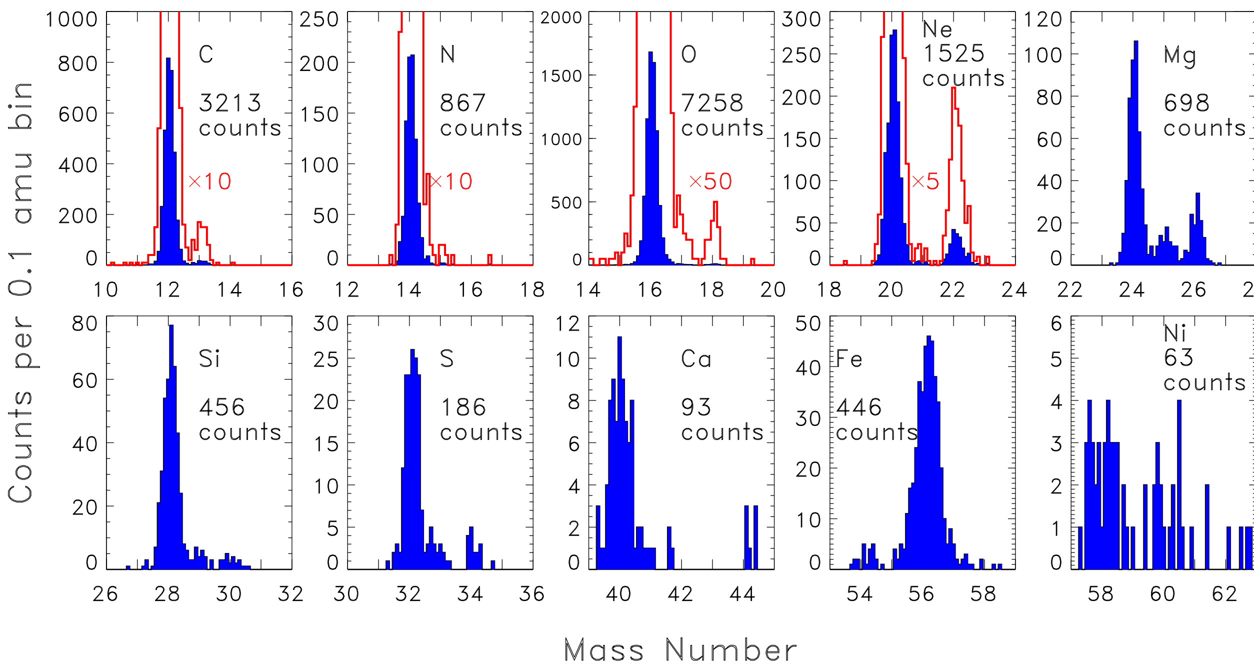

Figure 1: Mass histograms (*shaded*) from SIS, accumulated from 11/14/98 5:00 to 11/16/98 0:00. Views expanded by the factors indicated (*solid lines*) are also shown.

Isotope abundances were obtained for the nine largest SEP events observed by SIS between the launch of ACE in August 1997 and November 1998 by counting events in the peaks of the mass histograms (as in Figure 1), ignoring the effects of small tails in the distributions. The exact time periods used in this analysis are given in Leske et al. (1999b), with the energy intervals for each element (typically tens of MeV/nucleon) listed in Leske et al. (1999a). Using measured quiet-time intensities in SIS through November 1998, the background counts expected due to galactic cosmic rays and anomalous cosmic rays have been subtracted from these data. The quiet time background in these relatively large events is small, ranging from 0.41% to 6.4% of the SEP Ne, for example, depending on the intensity of the SEP event. Small corrections of $\lesssim 5\%$ were applied to correct relative isotopic abundances measured in equal ranges to equal energy per nucleon intervals.

3 Results and Discussion:

Figure 2 compares the isotope abundance ratios measured in these and earlier SEP events to the Fe/O ratio (Cohen et al., 1999b) measured in the same events. Large, statistically significant differences from the solar system standard values (Anders & Grevesse, 1989) are evident in a number of cases. In general, these deviations seem reasonably well correlated with the Fe/O ratio. Note that some of the earlier measurements (e.g., Dietrich & Simpson, 1979, 1981; Simpson et al., 1983) are actually averages over several solar events, and given the event-to-event variability, this may contribute to some of the scatter.

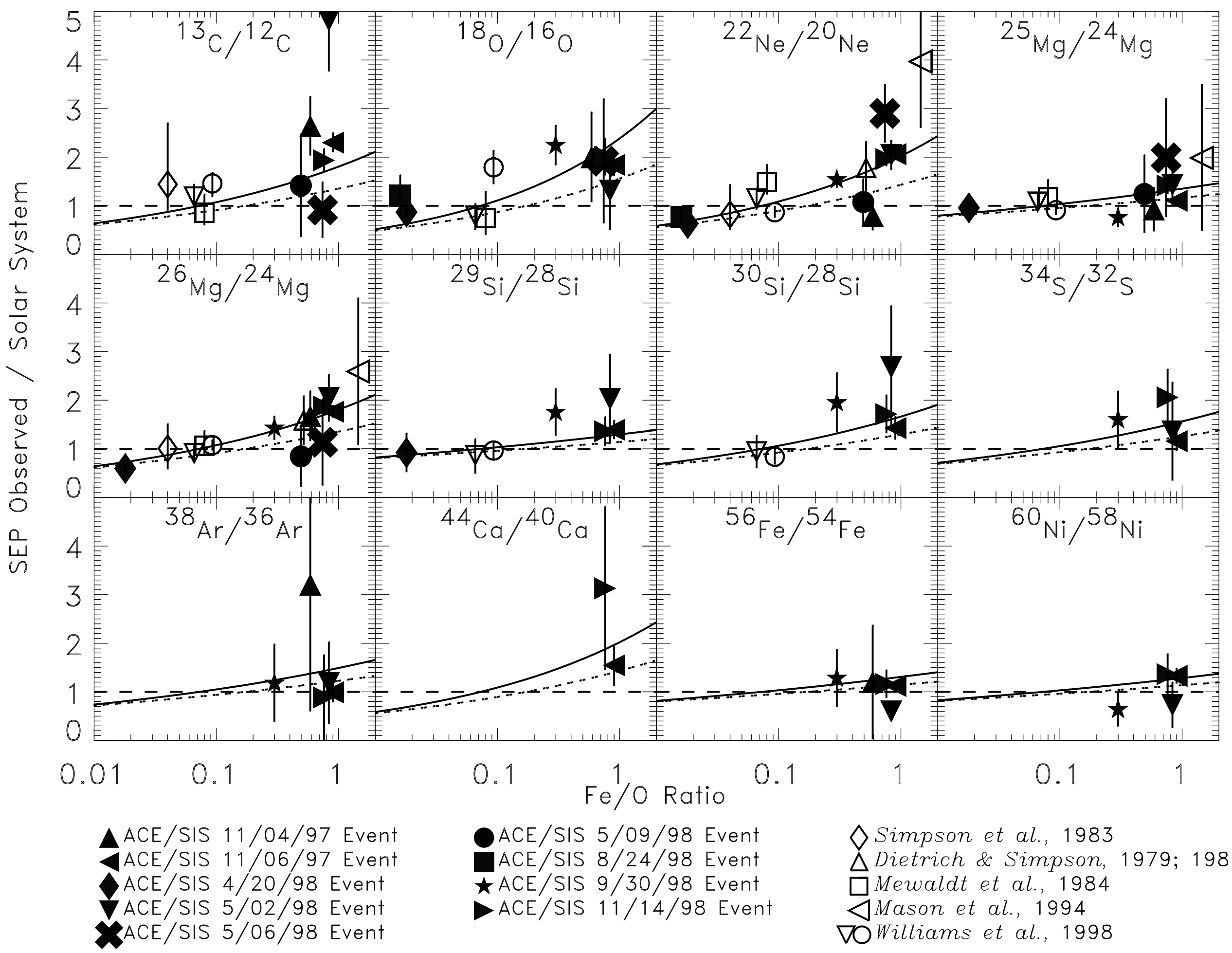

Figure 2: The isotope abundance ratios normalized to solar system values plotted vs. the observed Fe/O ratios. Preliminary values for ACE/SIS data (*filled symbols*) are from the indicated SEP events, with references for other data (*open symbols*) given in the legend. The dotted and solid curves show possible expected correlations for the ratios (see text). The dashed line indicates no deviation from the standard solar system values (Anders & Grevesse, 1989).

If one assumes that the elemental abundance variations scale as $(Q/M)^\gamma$, with a different power law index, γ, for each SEP event (Breneman & Stone, 1985), and that the Fe/O ratio is representative of the elemental fractionation, then an estimate for γ is given by (Mewaldt & Stone, 1989):

$$\gamma_{est} = \frac{\ln[(\mathrm{Fe/O})_{SEP}/(\mathrm{Fe/O})_{corona}]}{\ln[(Q/M)_{\mathrm{Fe}}/(Q/M)_{\mathrm{O}}]}, \tag{1}$$

assuming that the average SEP Fe/O ratio is that of the solar corona. For two isotopes of an element with the same value of Q but different masses M_1 and M_2, equation (1) implies that there should be mass fractionation, with the expected SEP M_2 to M_1 abundance ratio given by $(M_1/M_2)^\gamma$ times the corresponding coronal abundance ratio. (Note that as defined above, $\gamma < 0$ for Fe-rich events.)

For most of the SEP events shown in Figure 2, the Q/M values for Fe and O are not measured at the energies of the SIS isotope measurements. Using the charge states found in earlier gradual events at similar energies (Leske et al., 1995), equation (1) yields the predicted mass fractionation as a function of Fe/O given by the dotted curves in Figure 2. However, for those events which are likely to be impulsive (Mason et al., 1994; Cohen et al., 1999b) the ionic charge states are expected to be greater than in gradual events (Luhn et al., 1987). Also, in deriving equation (1), it was implicitly assumed that the elemental fractionation associated with the first ionization potential (FIP) effect is the same magnitude in the SEP event as it is between the photosphere and corona, but the size of the FIP fractionation is known to vary from event to event (Garrard & Stone, 1994). The $(Fe/O)_{SEP}$ value used in equation (1) must therefore be adjusted to represent only the Q/M fractionation, not any variation in this ratio due to atypical FIP fractionation. When the higher charge states and lower FIP fractionation inferred from SIS measurements in the 6 November 1997 event (Cohen et al., 1999a) are used in equation (1), mass fractionation shown by the solid curve in Figure 2 is expected. The solid and dotted curves thus illustrate some of the possible scatter in the correlations that might be attributed to charge state and FIP fractionation differences among the various events.

In spite of the scatter, it is clear that ratios such as ^{22}Ne/^{20}Ne and ^{26}Mg/^{24}Mg tend to be greater at higher Fe/O ratios, as predicted. Also, ratios with greater relative mass differences, such as ^{13}C/^{12}C, ^{18}O/^{16}O, ^{22}Ne/^{20}Ne, and ^{26}Mg/^{24}Mg, reach higher enhancement levels than those with smaller relative mass differences, such as ^{56}Fe/^{54}Fe and ^{60}Ni/^{58}Ni, again as expected.

It is possible to select elemental ratios other than the commonly-used Fe/O ratio which are more appropriate for isolating Q/M fractionation from FIP and charge state effects. By comparing the isotope ratios to an element ratio where both elements have either high-FIP or low-FIP, scatter due to differences in the degree of FIP fractionation is eliminated. Also, by choosing elements whose mean charge states are not expected to vary much over a broad temperature interval, scatter due to charge state differences may be greatly reduced. As discussed in more detail elsewhere (Cohen et al., 1999b; Mewaldt et al., 1999), Na and Mg fit both these criteria. As shown by Mewaldt et al. (1999), the ^{22}Ne/^{20}Ne ratio, for example, is much better correlated with the Na/Mg ratio than with the Fe/O ratio shown here. Subject to the FIP and charge state variations discussed earlier, both the isotopic and elemental fractionation appear to be governed by the same Q/M-dependent process.

Acknowledgments: This research was supported by NASA at the California Institute of Technology (under grant NAG5-6912), the Jet Propulsion Laboratory, and the Goddard Space Flight Center.

References

Anders, E. & Grevesse, N., 1989, Geochim. Cosmochim. Acta, 53, 197
Breneman, H. H. & Stone, E. C., 1985, ApJL, 299, L57
Cohen, C. M. S., et al., 1999a, Geophys. Res. Lett., 26, 149
Cohen, C. M. S., et al., 1999b, Geophys. Res. Lett., submitted
Dietrich, W. F. & Simpson, J. A., 1979, ApJL, 231, L91
Dietrich, W. F. & Simpson, J. A., 1981, ApJL, 245, L41
Garrard, T. L. & Stone, E. C., 1993, Proc. 23rd ICRC (Calgary), 3, 384
Garrard, T. L. & Stone, E. C., 1994, Adv. Space Res., 14, (10)589
Leske, R. A., Cummings, J. R., Mewaldt, R. A., Stone, E. C., & von Rosenvinge, T. T., 1995, ApJL, 452, L149
Leske, R. A., et al., 1999a, Geophys. Res. Lett., 26, 153
Leske, R. A., et al., 1999b, Geophys. Res. Lett., submitted
Luhn, A., Klecker, B., Hovestadt, D., & Möbius, E., 1987, ApJ, 317, 951
Mason, G. M, Mazur, J. E., & Hamilton, D. C., 1994, ApJ, 425, 843
Mewaldt, R. A., Spalding, J. D., & Stone, E. C., 1984, ApJ, 280, 892
Mewaldt, R. A. & Stone, E. C., 1989, ApJ, 337, 959
Mewaldt, R. A., et al., 1999, Proc. 26th ICRC (Salt Lake City), paper SH 1.4.17
Reames, D. V., 1995, Adv. Space Res., 15, (7)41
Simpson, J. A., Wefel, J. P., & Zamow, R., 1983, Proc. 18th ICRC (Bangalore), 10, 322
Stone, E. C., et al., 1998, Space Sci. Rev., 86, 357
Williams, D. L., Leske, R. A., Mewaldt, R. A., & Stone, E. C., 1998, Space Sci. Rev., 85, 379