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Solar Isotopic Composition as Determined Using Solar Energetic Particles

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Abstract Solar energetic particles (SEPs) provide a sample of the Sun from which solar composition may be determined. Using high-resolution measurements from the Solar Isotope Spectrometer (SIS) onboard NASA's Advanced Composition Explorer (ACE) spacecraft, we have studied the isotopic composition of SEPs at energies $\geq$20 MeV/nucleon in large SEP events. We present SEP isotope measurements of C, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni made in 49 large events from late 1997 to the present. The isotopic composition is highly variable from one SEP event to another due to variations in seed particle composition or due to mass fractionation that occurs during the acceleration and/or transport of these particles. We show that various isotopic and elemental enhancements are correlated with each other, discuss the empirical corrections used to account for the compositional variability, and obtain estimated solar isotopic abundances. We compare the solar values and their uncertainties inferred from SEPs with solar wind and other solar system abundances and find generally good agreement.

Keywords Sun: abundances · Sun: particle emission · Sun: coronal mass ejections (CMEs) · Sun: flares

1 Introduction

The Sun's composition may be determined using samples of solar material in the form of either the solar wind or solar energetic particles (SEPs), and each approach has its own challenges. In situ solar wind composition measurements typically require detailed knowledge

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of instrument response functions, efficiencies, and backgrounds, whereas SEP abundances are often distorted by fractionation processes during particle acceleration or transport. It is therefore valuable to compare solar abundances obtained from both types of studies.

The seed material for gradual SEP events is thought to be suprathermal solar wind or coronal material, possibly supplemented by flare particles or remnant material from earlier impulsive events (Tylka et al. 2005; Cane et al. 2003), accelerated by large shocks driven by fast coronal mass ejections (Reames 1995a). After correcting measured SEP elemental abundances for fractionation associated with acceleration and transport (Breneman and Stone 1985; Garrard and Stone 1993) or averaging over many events (Reames 1995b), estimates of the underlying solar elemental composition have been obtained. Similar analyses have been used in the past to determine the solar isotopic composition for a few elements (Mewaldt and Stone 1989; Williams et al. 1998).

Our previous studies using the Solar Isotope Spectrometer (SIS) on the Advanced Composition Explorer (ACE) have found large enhancements and event-to-event variability in SEP isotopic abundance ratios (see, e.g., Leske et al. 2001b, 2003, and references therein) with good correlations between various elemental and isotopic abundances. In the present work, we report ACE/SIS isotopic abundance measurements for C, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni in as many as 49 individual SEP events. Using the observed correlations we empirically correct for the compositional variability and derive solar isotopic abundances from SEPs.

2 Observations and Analysis

The SIS instrument uses the dE/dx versus residual energy technique in a pair of silicon solid-state detector telescopes to obtain the nuclear charge, Z, mass, M, and total kinetic energy, E, for particles with energies of $\sim$10 to $\sim$100 MeV/nucleon (Stone et al. 1998). For this study, we examined all SEP events with high-energy heavy ion intensities large enough to yield statistically meaningful isotope abundances for at least ^{22}Ne/^{20}Ne and ^{26}Mg/^{24}Mg. This selection resulted in 49 large SEP events, $\sim$50% more than were used in our earlier analysis (Leske et al. 2003). During the very highest rate periods, mass resolution is degraded by chance coincidences between heavy ions and low energy protons. Therefore, time periods near the peaks of the 10 largest events (with $\sim$20–60 MeV/nucleon oxygen intensities exceeding $\sim 10^{-3}$ (cm^2 sr s MeV/nucleon)$^{-1}$) were not used for the isotopic analysis. Mass resolution depends on Z and E; for the species and energies studied here it ranges from $\sim$0.15 to $\sim$0.3 amu, as illustrated by the well-resolved mass peaks in Fig. 1. Obtaining event-integrated isotope abundance ratios from these data is straightforward; further analysis details are given elsewhere (Leske et al. 1999a, 1999b). At present we do not attempt to isolate ^{15}N, ^{17}O, or ^{21}Ne, but these species may be measurable at high energies in some events with further work.

Deriving the source composition is complicated by the event-to-event variability of SEP isotopic abundances, as is evident from the two neon mass histograms shown in Fig. 2. Note that the ^{22}Ne/^{20}Ne abundance ratio, relating two species that differ by only 10% in mass, can vary by a factor of $\sim$4 from event to event.

If there is any variation in an isotopic abundance ratio with energy, it is generally small compared with statistical uncertainties or compared with the deviation of that ratio from the solar wind value, at least over the energy interval of our measurements. Examples for the case of the ^{22}Ne/^{20}Ne ratio in the two extreme events shown in Fig. 2 are illustrated in Fig. 3. Within statistical uncertainties, no energy dependence is evident in either case.

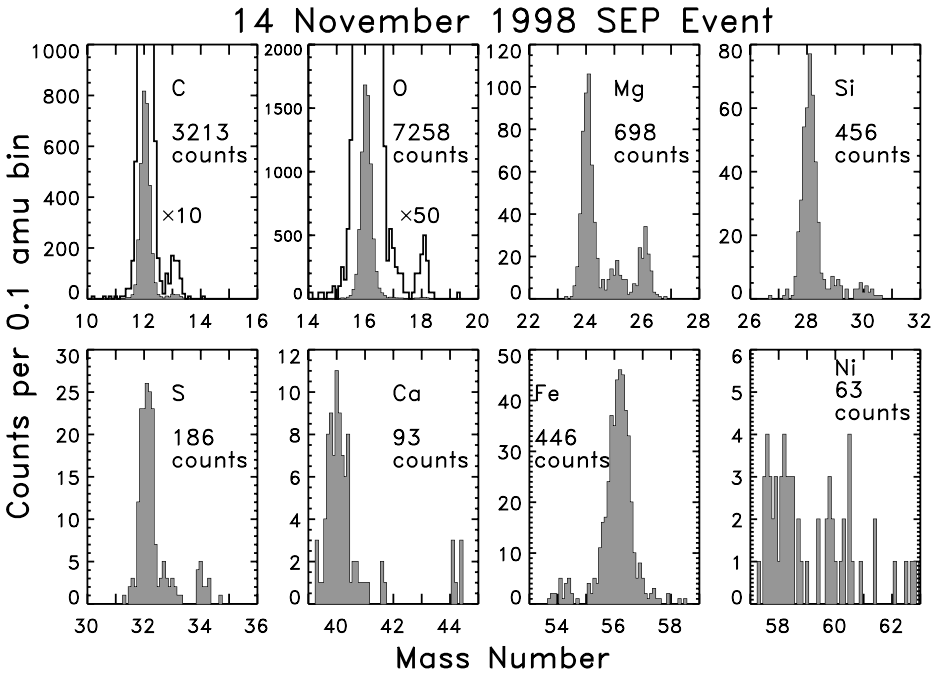

Fig. 1 Selected mass histograms from ACE/SIS for $E \gtrsim 20$ MeV/nucleon during the 14 November 1998 SEP event. Expanded views by the factors indicated are used to improve the visibility of the ^{13}C and ^{18}O peaks

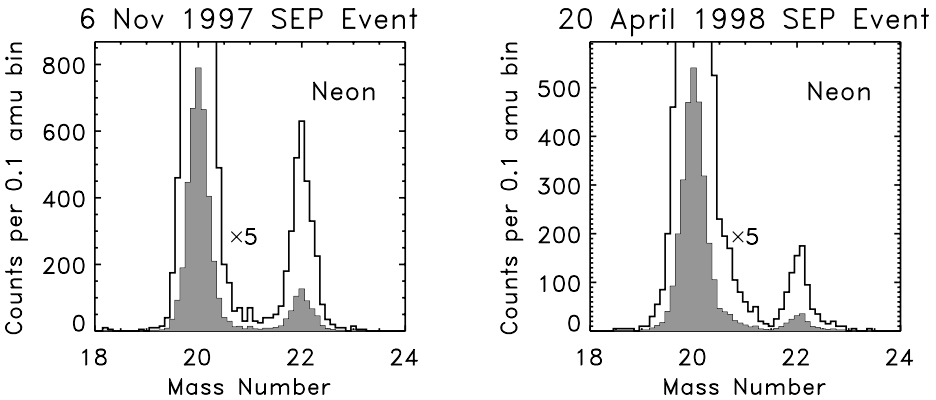

Fig. 2 Neon mass histograms from the 6 November 1997 SEP event (*left*) and 20 April 1998 event (*right*), plotted with the ^{20}Ne peaks at the same height. The ^{22}Ne/^{20}Ne ratio is clearly different in the two events, as seen more easily by the factor of 5 expanded views

The ^{22}Ne/^{20}Ne ratio for the 6 November 1997 event is significantly enhanced over the solar wind value throughout the SIS energy interval, while it is consistently somewhat depleted in the 20 April 1998 event. The Fe/O ratio in this latter event varies strongly with energy, dropping by a factor of ∼50 between 10 and 40 MeV/nucleon (Tylka et al. 2000). Both the Fe and O spectra are essentially exponentials (rather than power laws) in energy per

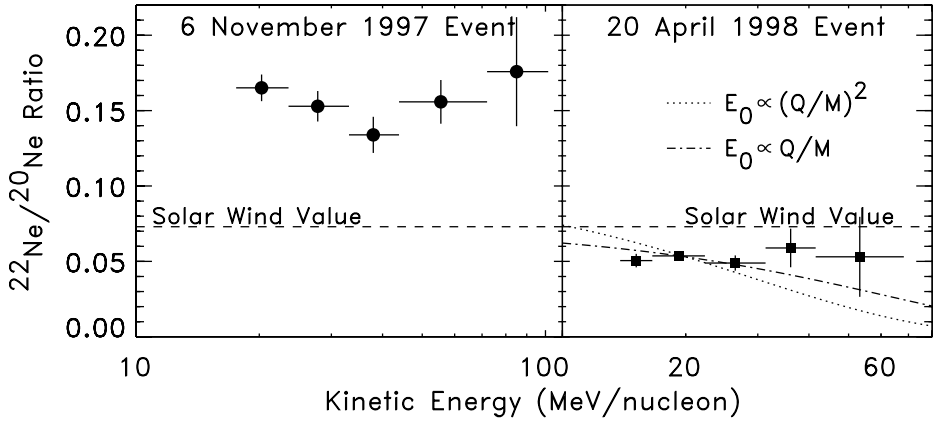

Fig. 3 The SEP ^{22}Ne/^{20}Ne isotopic abundance ratio plotted versus energy for the 6 November 1997 event (*left*) and the 20 April 1998 event (*right*). Also shown is the expected energy dependence in the 20 April 1998 event for spectra that are exponential in energy per nucleon with e-folding energies E_0 scaling as $(Q/M)^2$ (*dotted curve*) or Q/M (*dot-dashed curve*). The curves were normalized at 20 MeV/nucleon, using a fitted E_0 for ^{20}Ne of 6.3 MeV/nucleon and assuming the mean Q for ^{20}Ne is the same for ^{22}Ne. The *horizontal dashed* line marks the solar wind ^{22}Ne/^{20}Ne value

nucleon. The large energy dependence of the abundance ratios observed in such events is often due to spectra with e-folding energies which scale with the ratio of the mean ionic charge, Q, to mass, M, and Q/M is lower for Fe than for O. Shock acceleration theory (Li et al. 2005) suggests these e-folding energies should scale as $(Q/M)^2$. However in this particular event, analysis of elemental spectra (Tylka et al. 2000) shows the scaling goes more nearly as Q/M. As shown in Fig. 3, e-folding energies scaling as $(Q/M)^2$ would result in a larger energy dependence in the ^{22}Ne/^{20}Ne ratio than can be accommodated by the data, and while Q/M scaling yields more energy dependence than necessary to fit the data, it is not inconsistent with the 1-σ uncertainties. Since any energy dependence is expected to be quite small over our energy interval, for the present study we assume all isotopic abundance ratios are independent of energy.

Earlier studies (Breneman and Stone 1985) have shown that SEP heavy ion elemental abundance ratios are also quite variable from event to event and scale approximately as a power law in Q/M, with a power law index which itself varies from event to event. Any process which fractionates elements based on Q/M must also affect isotopes with different M, and there should be a predictable correlation between elemental and isotopic abundances. Power-law fractionation in Q/M implies that the enhancement or depletion of any measured SEP abundance ratio X_1/X_2, when compared with the abundance ratio of any two reference species R_1/R_2, should be:

$$\frac{(X_1/X_2)_{SEP}}{(X_1/X_2)_{solar}} = \left(\frac{(R_1/R_2)_{SEP}}{(R_1/R_2)_{solar}}\right)^{\frac{\ln[(Q/M)_{X_1}/(Q/M)_{X_2}]}{\ln[(Q/M)_{R_1}/(Q/M)_{R_2}]}}. \quad (1)$$

We find that isotopic abundances are indeed correlated with elemental abundances, as illustrated in Fig. 4. To compare these correlations with those expected from (1) the mean ionic charge states Q of the species involved must be known. It is reasonable to assume that $\langle Q(^{22}\mathrm{Ne})\rangle = \langle Q(^{20}\mathrm{Ne})\rangle$, so the values of $Q(X_1)$ and $Q(X_2)$ in (1) factor out, but this will not be true for the charge states of Fe and O or Na and Mg used in Fig. 4. For most

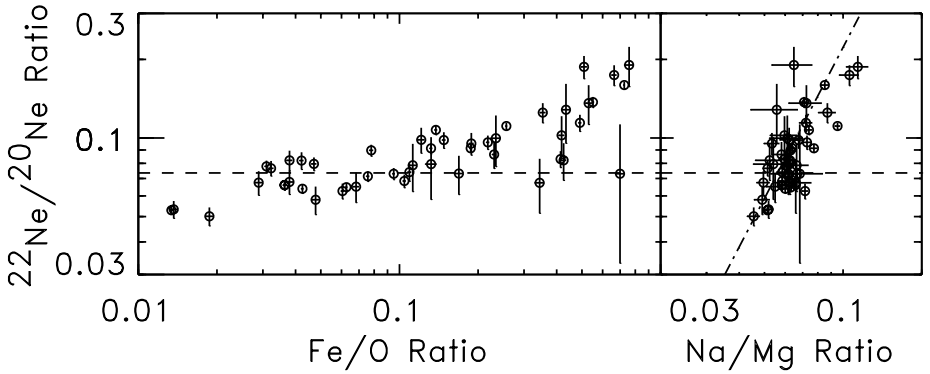

Fig. 4 The SEP ^{22}Ne/^{20}Ne isotopic ratio plotted versus the Fe/O (*left*) and Na/Mg (*right*) elemental abundance ratios. The *diagonal line* shows the correlation expected from (1), assuming $\langle Q(\mathrm{Na})\rangle = 9$ and $\langle Q(\mathrm{Mg})\rangle = 10$. The *horizontal dashed line* marks the solar wind ^{22}Ne/^{20}Ne value

SEP events Q is not measured at energies of tens of MeV/nucleon. Lower energy charge-state measurements may not apply as heavy elements often exhibit energy-dependent charge states (Oetliker et al. 1997; Klecker et al. 2006; Popecki 2006), while those higher energy charge state measurements that do exist show considerable event-to-event variability (see, e.g., Leske et al. 2001a and references therein; Labrador et al. 2005). Also, in the derivation of (1) it was implicitly assumed that any elemental fractionation associated with the first ionization potential (FIP) is the same magnitude in the SEP event as it is in the solar source material. However, the size of the FIP effect in SEP events (Garrard and Stone 1994; Mewaldt et al. 2000; Slocum et al. 2003), in the corona (Widing and Feldman 2001), and in solar wind (von Steiger et al. 2000) is variable, which can affect certain elemental but not isotopic ratios and may blur the expected correlations.

The ^{22}Ne/^{20}Ne ratio generally correlates better with Na/Mg than with Fe/O. Note that those events in Fig. 4 with ^{22}Ne/^{20}Ne values near that of the solar wind exhibit Fe/O ratios which span nearly 2 orders of magnitude, while nearly all their Na/Mg ratios are tightly clustered around the standard solar system value of 0.056 (Lodders 2003). Na and Mg have similar FIP values, and their charge states are much less variable than those of Fe. As noted in Cohen et al. (1999), both Na and Mg ions should have 2 electrons attached over a broad range of coronal temperatures (Arnaud and Rothenflug 1985). The dot-dashed line in Fig. 4 shows the expected correlation if $\langle Q(\mathrm{Na})\rangle = 9$ and $\langle Q(\mathrm{Mg})\rangle = 10$. This very simple model provides a good first order fit to most of the data.

The predicted correlations are very sensitive to Q/M for reference ratios involving similar values of Q/M; changing $Q(\mathrm{Na})/Q(\mathrm{Mg})$ or the mean mass of Mg by only 1% changes the expected slope by ∼20% (Leske et al. 2001b). Even if Q could be measured to this accuracy at SIS energies, it is Q at the time of fractionation that matters, which may differ from that at 1 AU if fractionation happens early and if stripping occurs in acceleration through the corona (see, e.g., Barghouty and Mewaldt 2000). The sensitivity of the correlations to variability in the Na and Mg charge states or mean Mg mass may account for the scatter remaining in the right panel of Fig. 4.

Since the mean Q should be the same for isotopes of the same element, if we use an isotope ratio as the reference value in (1) the charge states factor out and also the mass is fixed, so we might expect a tighter correlation. This is illustrated by the plot of ^{22}Ne/^{20}Ne versus ^{26}Mg/^{24}Mg in Fig. 5. Most of the events with small uncertainties agree very well with

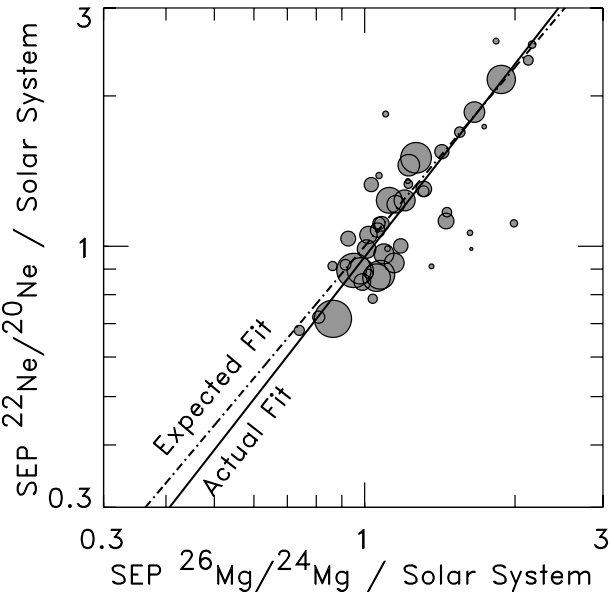

Fig. 5 The $^{22}Ne/^{20}Ne$ versus $^{26}Mg/^{24}Mg$ isotopic ratios in each of the 49 SEP events, normalized to standard solar system values (Lodders 2003). The correlation expected using (1) and the actual fit are also shown. The *symbol* diameters scale inversely with the size of the uncertainties (so larger points have a greater significance)

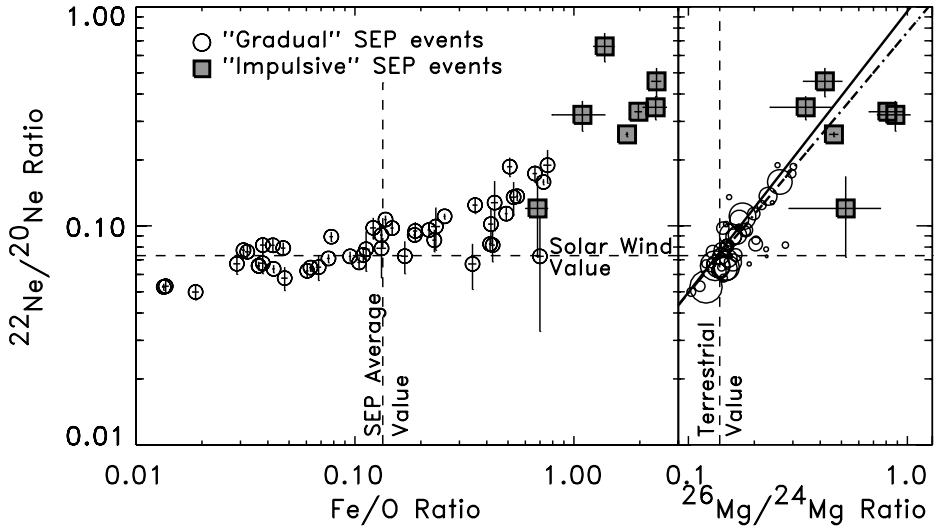

Fig. 6 The SEP $^{22}Ne/^{20}Ne$ isotopic ratio plotted versus the Fe/O (*left*) and $^{26}Mg/^{24}Mg$ (*right*) abundance ratios for both gradual and impulsive SEP events. *Diagonal lines* are the same as in Fig. 5

the expected line, and the actual fit differs from the expected correlation by no more than ∼7% over the entire range of measured values.

The few impulsive (i.e., ^{3}He-rich) events we have observed at energies of tens of MeV/nucleon with good heavy-ion statistics tend to be extremely fractionated and variable, with $^{22}Ne/^{20}Ne$ as much as 9 times the solar wind value and $^{26}Mg/^{24}Mg$ enhanced by more than 6 times the terrestrial value. Such extreme isotopic fractionation in impulsive events has also been reported at lower energies (Mason et al. 1994; Dwyer et al. 2001). In Fig. 6, nearly

all the impulsive events shown have an Fe/O ratio higher than in gradual events, as has long been known (e.g., Reames et al. 1994). The very tight correlation between $^{22}Ne/^{20}Ne$ and $^{26}Mg/^{24}Mg$ (Fig. 5) seen in gradual events seems absent from impulsive events, with individual events scattered about, but not on, the correlation line. Peculiar abundances in individual impulsive events that are not simply correlated with Q/M may be due to resonant plasma heating of the source material (see, e.g., Mason et al. 2002 and references therein). However, since Fe-rich (and therefore from Fig. 4 $^{22}Ne/^{20}Ne$-rich) gradual events are thought to be contaminated by or even dominated by impulsive flare material (Tylka et al. 2005; Cane et al. 2003), one might expect both event classes to show similar fractionation patterns. Perhaps the very large impulsive events we observe with SIS are compositionally peculiar compared to a typical impulsive event. Or the scatter in individual impulsive event composition may suggest that the impulsive contribution to gradual events represents some sort of average impulsive material—either a temporal average over several impulsive events (Tylka et al. 2005) or a spatial average resulting from a large shock passing through spatially inhomogeneous flare material.

3 Results

The SEP abundance values for 11 isotope ratios for elements from C to Ni are shown plotted versus $^{26}Mg/^{24}Mg$ in Fig. 7, with the correlations expected from (1) indicated by diagonal lines. The data roughly agree with the expected trends for Ne, Mg, and Si. Elements heavier than Si tend to have fewer data points and lower statistical significance, and the correlation

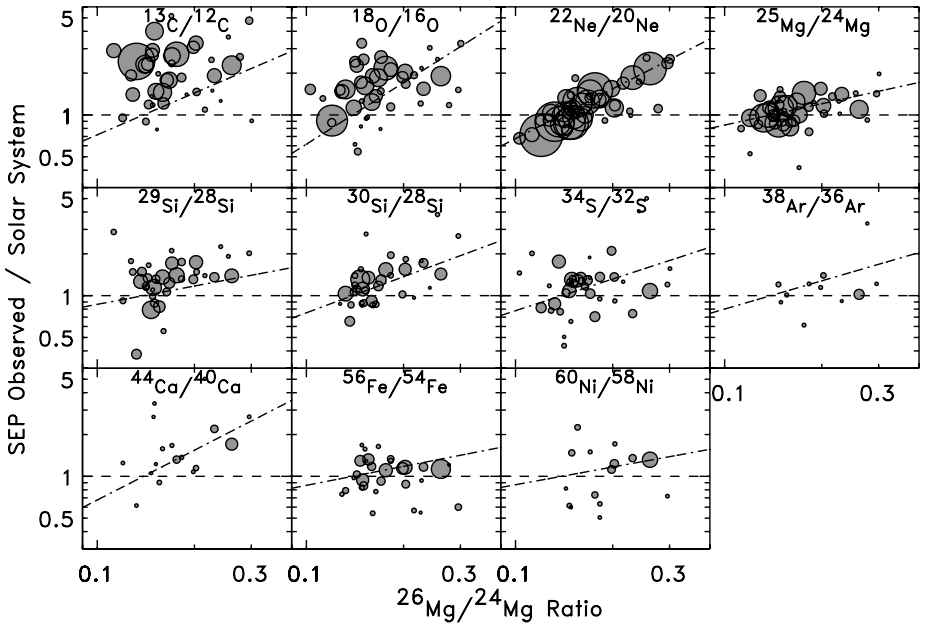

Fig. 7 Eleven SEP isotope abundance ratios (normalized to standard solar system abundances, Lodders, 2003) in up to 49 SEP events plotted versus the $^{26}Mg/^{24}Mg$ ratio. *Diagonal lines* show the correlations expected using (1), where the different slopes arise from the different mass ratios. *Symbol* diameters scale inversely with the size of the uncertainties

between the actual fractionation and the expected trends is less clear. The correlations may break down for species with Q/M far from that of the Mg reference ratio if the actual dependence on Q/M is not a simple power law as we assumed. At lower Z, ^{13}C is often enhanced or ^{12}C is depleted in SEP events relative to terrestrial abundances, but the reason for this is not understood. Higher ^{13}C values do not appear to be due to spillover from ^{12}C, as the two mass peaks are generally well separated (Leske et al. 1999a).

Using ^{26}Mg/^{24}Mg as the reference ratio in (1) with its solar value taken to be the terrestrial value (Lodders 2003), and assuming Q is the same for different isotopes of the same element, we obtain the solar isotope ratios for each SEP event. Averaging over all the SIS measurements for each isotope ratio results in the SEP-derived solar values shown in Fig. 8. We also show the weighted average without correcting for fractiona-

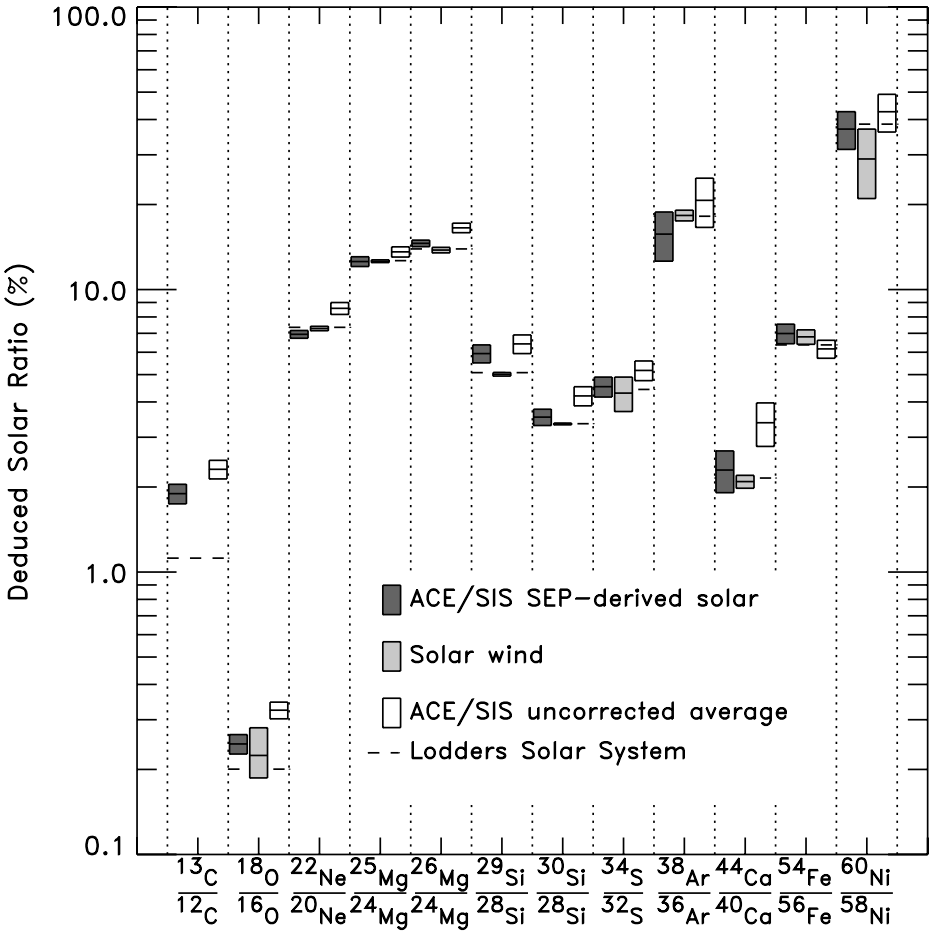

Fig. 8 Average solar isotopic abundance ratios from SIS SEP measurements after correcting for fractionation (*dark grey boxes*). The ^{26}Mg/^{24}Mg ratio served as the reference value in (1) for everything other than ^{26}Mg/^{24}Mg, for which ^{22}Ne/^{20}Ne was used. For comparison, averages without fractionation corrections (*open boxes*), standard solar system values (*dashed lines*; Lodders 2003) and measured solar wind values (*light grey boxes*; Kallenbach 2001; Wimmer-Schweingruber et al. 2001; Ipavich et al. 2001; Wimmer-Schweingruber 2002; Karrer et al. 2007) are shown

tion, which may be more appropriate for cases where the data may not follow the expected fractionation correlations or for studies more interested in arriving fluences of various species rather than source composition. For comparison Fig. 8 also shows standard solar system values (Lodders 2003) and existing solar wind values (Kallenbach 2001; Wimmer-Schweingruber et al. 2001; Ipavich et al. 2001; Wimmer-Schweingruber 2002; Karrer et al. 2007). As new results from Genesis become available the solar wind values may change, although preliminary results for the $^{22}Ne/^{20}Ne$ ratio (Grimberg et al. 2007) appear to be consistent with the solar wind values plotted here. Enhancement factors over standard abundances for our SEP-derived solar values and for solar wind values are shown in Fig. 9.

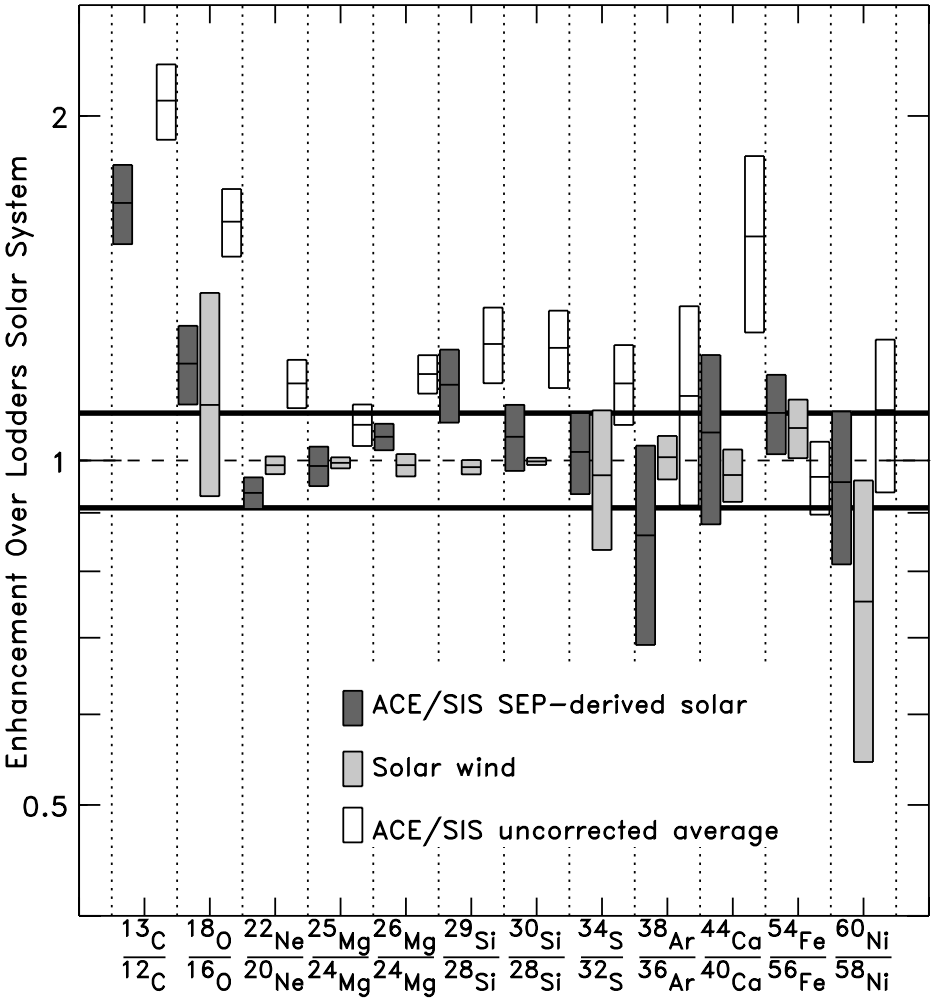

Fig. 9 Ratio of deduced source values (see Fig. 8) to the standard solar system values (Lodders 2003). SEP measurements after correcting for fractionation (*dark grey boxes*), SEP averages without fractionation corrections (*open boxes*), and measured solar wind values (*light grey boxes*; Kallenbach 2001; Wimmer-Schweingruber et al. 2001; Ipavich et al. 2001; Wimmer-Schweingruber 2002; Karrer et al. 2007) are shown. *Solid horizontal lines* indicate ±10% deviation from the standard solar system values

Although our fractionation correction makes simplifying assumptions, the resulting solar abundances mostly appear to be quite reasonable. All but 2 values are within 2σ of the standard "solar system" values (Lodders 2003) (which are actually terrestrial values except for Ne and Ar, for which solar wind values were used) and most are within 10% of the standard values (Fig. 9). Our results also agree well with the average values shown for the solar wind, which can be compositionally quite variable (Raymond et al. 2001). Performing our analysis on subsets of the SEP events selected on the basis of iron enrichment or spectral shape (as done for elemental abundances in Cohen et al. 2007) naturally increases the uncertainties on our derived solar abundances, but does not significantly change their values. In particular, our ^{13}C measurements suggest that some additional process affects fractionation of this isotope or that fractionation is more than just a simple power law for all Q/M. For several ratios, uncertainties on our SEP-derived solar abundances are comparable to or better than those presently obtained from the solar wind. Additional SEP events may reduce the uncertainties for the heaviest species where there are still only a few measurements, but a better theoretical understanding of the mass fractionation process would allow much further progress. Continued study of puzzles such as the frequent enhancement of ^{13}C may provide clues to the nature of the fractionation process.

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