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Examining the abundances of rare elements in solar energetic particle events

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Abstract. Using data accumulated with the Solar Isotope Spectrometer on ACE during 27 large solar energetic particle (SEP) events the effects of charge-to-mass (Q/M) fractionation on rare elements are examined. In an attempt to correct for these fractionation effects and obtain preliminary estimates of the coronal abundances of K, Ti, Cr, Mn, Co, Ni, Cu, and Zn, the SEP events are classified according to their Fe/Si ratio. The data from all events within an Fe/Si category are summed and the rare element abundances extracted over an energy interval of 20 to 65 MeV/nucleon. We estimated the apparent Q/M fractionation, corrected for it, and obtained initial results which are encouraging.

1 Introduction

Obtaining the coronal abundance of rare elements such as K, Ti, Mn, Co, and Cu through spectroscopy is difficult. Calculations of ionization equilibrium are complicated by coronal conditions that are typically not in local thermal equilibrium. Additionally, the charge state distribution of these elements is broad resulting in very low abundances for a given rare ion, making detection difficult.

Rare elements can be accurately measured in solar energetic particle (SEP) events. By accounting for fractionation effects that can alter the SEP composition from that of the coronal source material, the coronal abundances of rare elements can be inferred from SEP measurements. A difficulty arises in that the fractionation effects vary from event to event. The two primary fractionation processes are typically expressed as functions of the first ionization potentials (FIP; Cook et al. (1984) and Meyer (1985)) and the charge-to-mass ratios (Q/M) of the elements (see, e.g., Breneman and Stone (1985)). One manner of dealing with these effects is to examine ratios of elements with similar FIP and Q/M values as was done by Cohen et al. (2001). The results of their work (Table 1) are, for most elements, consistent with the SEP measurements reported by Breneman and Stone (1985) and Reames (1995). However, such a method of analysis does not yield a set of abundances relative to a common element such as Si.

Another way of accounting for the Q/M fractionation was used by Garrard and Stone (1993). After averaging the measured composition of many events they determined the residual Q/M fractionation by comparing the measured abundances of elements with FIPs less than 10 eV (low-FIP elements) to photospheric abundances as a function of Q/M and fitting a power law to the data. Since the FIP fractionation differentiates between elements with FIPs greater than 10 eV and those less than 10 eV, by concentrating on low-FIP elements the effects of FIP-fractionation are not a concern. Garrard and Stone (1993) applied an emperical correction for the residual Q/M fractionation to the average SEP abundances to obtain the coronal composition.

Event-by-event corrections are difficult when examining rare elements as they are not abundant enough to measure in all individual events. For this work we attempt a compromise. Each SEP event examined is categorized by the degree of Q/M fractionation. The data from events within a given category are then summed to obtain statistically significant rare element abundances. These abundances are then corrected for the Q/M fractionation to obtain an initial estimate of the coronal composition for rare elements relative to a common element.

2 Instrumentation and Data Analysis

The data presented here are from the Solar Isotope Spectrometer (SIS; Stone et al. (1998)) on the ACE spacecraft. The SIS sensor contains two identical telescopes, each of which has two position-sensing matrix detectors followed by a stack of large-area silicon detectors. The matrix detectors allow the particle trajectories to be determined, which combined with the deposited energies measured by the stack detectors permit accurate determinations of nuclear charge, Z, mass, M,

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Table 1. Element Ratios Multiplied by 1000

Element Ratio	FIP (eV)*	Cohen et al. (2001)	Photospheric Grevesse and Sauval (1998)	Meteoritic Grevesse and Sauval (1998)
P/Si	10.49	5.12 ± 0.47	7.76 ± 0.75	10.00 ± 1.48
Cl/Si	13.00	1.66 ± 0.29	5.24 ± 0.78	5.25 ± 0.78
K/Ca	4.34	60.87 ± 4.78	58.87 ± 20.56	60.26 ± 2.84
Ti/Ca	6.82	38.79 ± 4.22	46.74 ± 6.97	38.90 ± 1.83
Cr/Fe	6.77	20.06 ± 0.85	14.76 ± 1.08	15.49 ± 0.36
Mn/Fe	7.44	12.55 ± 0.68	7.76 ± 0.56	10.72 ± 0.25
Co/Fe	7.86	3.88 ± 0.31	2.63 ± 0.26	2.57 ± 0.06
Ni/Fe	7.64	60.89 ± 1.42	56.23 ± 1.31	56.23 ± 1.31
Cu/Fe	7.73	0.69 ± 0.14	0.51 ± 0.05	0.62 ± 0.06
Zn/Fe	9.39	1.33 ± 0.21	1.26 ± 0.26	1.48 ± 0.14

* FIP values are for the elements in the numerator of the ratio

and total kinetic energy, E, to be made. The large geometry factor ($\sim$38 cm^2-sr) of SIS is key in obtaining statistically significant measurements of rare elements.

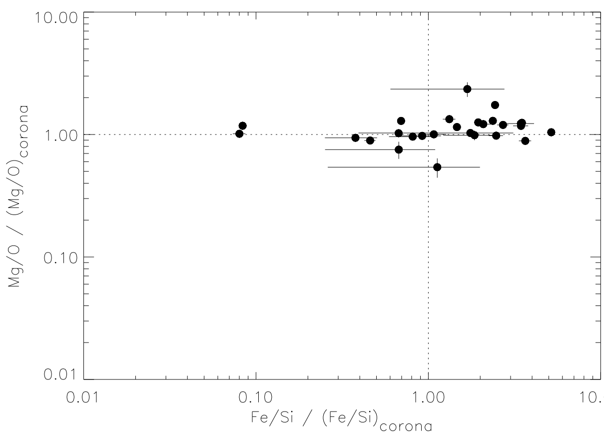

Fig. 1. Mg/O ratios versus Fe/Si ratios (normalized to coronal abundances as given in Reames (1995)) for each SEP event.

For each of the 27 large SEP events examined by Cohen et al. (2001) which occurred between November 1997 and January 2001, the Mg/O versus Fe/Si ratios, normalized to coronal values (Reames, 1995), are plotted in Figure 1. Mewaldt et al. (2000) suggest that the Mg/O ratio is a useful measure of the degree of FIP fractionation in an event because Mg is a low-FIP element and O is a high-FIP one and they have similar Q/M values over a large temperature range so the Q/M fractionation between them is small. These authors find Fe/Si is an adequate indicator of the degree of Q/M fractionation due to the different Q/M values and very similar FIP values of Fe and Si. It is apparent from Figure 1 that the variation in Q/M fractionation between the 27 events is substantial (Fe/Si varies by almost an order of magnitude) while the FIP fractionation flucutuates by approximately a factor of 4 (and mostly by $\lesssim$ 2x).

For this study we set aside the FIP fractionation issues by examining only elements with FIPs less than 10 eV. In a first attempt to account for the Q/M fractionation, the events are

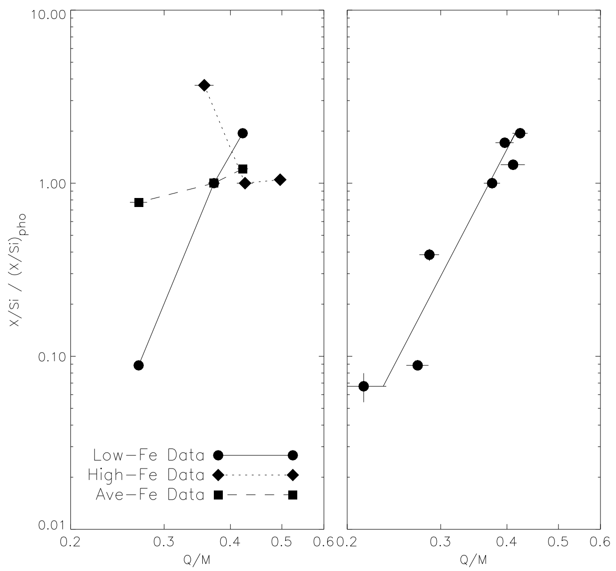

Fig. 2. Abundances relative to photospheric values (Grevesse and Sauval, 1998) (normalized to Si) as a function of the charge to mass ratio (Q/M) of the elements. The left panel shows data from the low-Fe, high-Fe, and average-Fe groups for Mg, Si, and Fe, using measured charge states from Leske et al. (2001). The right panel shows data from the low-Fe group data for Na, Mg, Al, Si, Ca, Fe, and Ni using measured charge states from Leske et al. (1995). A power law fit to the data in the right panel is indicated by the solid line.

grouped according to their Fe/Si ratio. Events with Fe/Si ratios within a factor of 2 of the coronal value are considered ‘average-Fe’ events. Those with Fe/Si less than half the coronal value are labeled ‘low-Fe’ events and those with Fe/Si ratios greater than twice the coronal values are ‘high-Fe’ events. The data from events within each category are summed and analyzed in the manner described by Cohen et al. (2001).

The charge states for Mg, Si, and Fe have been determined using data from the Mass Spectrometer Telescope (MAST) on the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) and the geomagnetic filter tech-

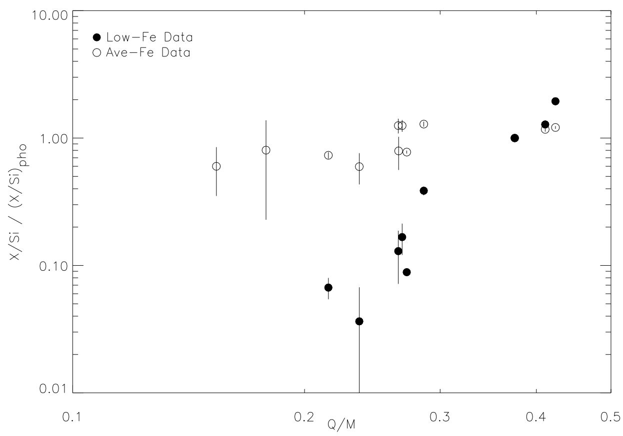

Fig. 3. Abundances as compared to photospheric values (Grevesse and Sauval, 1998) (normalized to silicon) for the low-Fe group and the average-Fe group data as a function of Q/M.

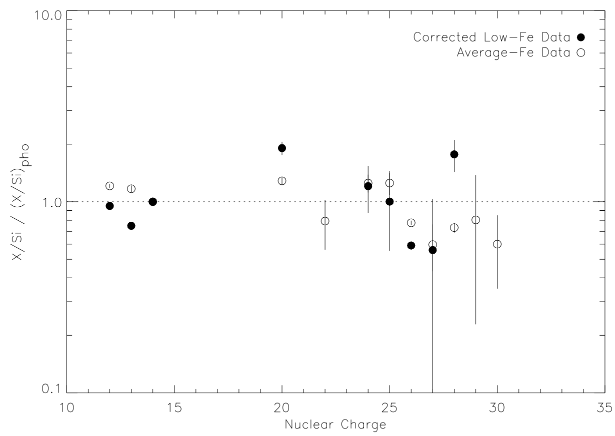

Fig. 4. Resulting abundances as compared to photospheric values (Grevesse and Sauval, 1998) (normalized to silicon) for the low-Fe group data, after correcting for Q/M fractionation, and the average-Fe group data.

nique by Leske et al. (2001)in SEPs at energies similar to those studied by SIS. The authors find a correlation between the charge states and the Fe/O ratio of events. Using their charge states found in high-Fe/O events for our high-Fe data and their charge states found in low-Fe/O events for our low-Fe and average-Fe data, we plot the relative abundances of Mg, Si, and Fe (normalized to photospheric values Grevesse and Sauval (1998)) as a function of Q/M in the left panel of Figure 2.

While the average-Fe and low-Fe data are organized by Q/M, the high-Fe data are not (possible reasons for this are discussed later). For the current investigation these high-Fe events are set aside and we focus on the average-Fe and low-Fe data. In the right panel of Figure 2, the abundances relative to photospheric values for Na, Mg, Al, Si, Ca, Fe, and Ni are plotted as a function of Q/M. Here, the charge states measured by Leske et al. (1995) are used because they include more low-FIP elements (note, the Leske et al. (1995) Mg, Si, and Fe charge states are consistent with those of Leske et al. (2001)). A power law is fit to the data and shown as a solid line on the plot. It is this fit that is used to correct for the Q/M fractionation of the low-Fe data.

To obtain charge states of the rare ions (K, Ti, Cr, Mn, Co, Cu, and Zn) a linear interpolation between the measured charge states of Si, Ca, Fe, and Ni as a function of nuclear charge was used. The low-Fe and average-Fe abundances for the low-FIP elements (Mg-Zn) as a function of Q/M are given in Figure 3. The resulting abundances after removing the Q/M fractionation (per Figure 2) from the low-Fe data are shown as a function of nuclear charge in Figure 4.

3 Discussion

While the results given in Figure 4 are encouraging, they are preliminary. The rare element abundances relative to Si as obtained here are consistent with photospheric values, but the uncertainties are large. For Mg, Al, Ca, Fe and Ni there are significant differences not only between the low-Fe and average-Fe results but also as compared to the photospheric values. There may be a small amount of Q/M fractionation present in the average-Fe data, suggested by the fact that Mg/Si and Al/Si are slightly enhanced, while Fe/Si and Ni/Si are depleted.

It is can be seen in Figure 2 that Ca, Fe, and Ni (at Q/M values of 0.29, 0.27, and 0.21, respectively) together do not agree well with a Q/M power law fit. It is possible that this is a result of combining the data from several SEP events. Although the events were grouped according to their Fe/Si abundance, the amount of Q/M fractionation still varies between the selected events. The fact that Ca, Fe and Ni deviate significantly from the fitted power law affects their derived corona values and so it is necessary to understand these differences.

The deviations of Ca, Fe and Ni could be an indication that the assumption of a power law in Q/M is not correct. Alternatively, it could be that the charge states measured at 1 AU are significantly different than the charge states of the ions at the time of Q/M fractionation. Especially in the high-Fe events there may be electron stripping between the time of the Q/M fractionation and the particles' arrival at 1 AU (Barghouty and Mewaldt, 1999). It is also important to note that the charge states used here are averages of distributions. If the Q/M fractionation is significant, it will alter the distributions, possibly resulting in substantially altered average charge states at 1 AU.

Another aspect that could affect the power law fit is that the average charge states used in Figure 2 are the average of those obtained in two 1992 SEP events. Since the average charge state is known to vary from event to event (Leske et al., 2001), it is possible that these values are not appropriate for the events studied here.

In addition to understanding more fully the trends seen in the low-Fe and average-Fe group abundances, it will be neccessary to address the FIP fractionation as well in order to obtain a full set of abundances. It is also important to unravel the complicated abundance and charge state patterns found in the high-Fe SEP events. Because of the strong fractionation present in these events, they often provide the most statistically accurate measurements of many rare elements.

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