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Correlated Elemental and Isotopic Variations in Solar Energetic Particles

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Abstract

We consider whether the observed fractionation of Ne isotopes recently reported in solar energetic particle (SEP) events is due to the same charge-to-mass dependent fractionation processes that apparently cause SEP elemental composition variations. We find that the observed correlation of the $^{22}Ne/^{20}Ne$ and Na/Mg ratios in nine large SEP events is consistent with a common fractionation process if the charge states of these ions are characteristic of a source temperature of ~1.5 to ~4 million degrees.

1 Introduction:

Measurements of the nine largest solar energetic particle (SEP) events observed since the launch of ACE in August 1997 have shown that a number of isotope abundance ratios, including $^{22}Ne/^{20}Ne$, can vary by a factor of ~3 to ~4 from event to event (Leske et al. 1999a, 1999b) – considerably more than had been expected based on measurements of the elemental composition of SEPs. Variations in the elemental composition are commonly assumed to indicate that the acceleration and/or transport of SEPs depends on particle rigidity, and therefore on the charge-to-mass ratio (Q/M) of the ions in the source plasma. Note that existing measurements show that in most large events SEP ions with Z>6 are not fully stripped, with the mean Q/M ratio of Fe in SEPs typically ~1/2 that of O. Measured SEP charge states in gradual SEP events are generally characteristic of a source temperature of ~2 MK, similar to coronal temperatures (see, e.g., Luhn et al. 1985, Leske et al. 1995), while in impulsive events the temperatures are somewhat higher (Luhn et al. 1987, Reames et al. 1995, Cohen et al. 1999a, b).

Breneman and Stone (1985) showed that the abundances of the elements from C to Ni in a given event, relative to SEP abundances averaged over many solar events, were ordered by the mean charge-to-mass ratio, <Q/M> measured at ~1 MeV/nuc (Luhn et al. 1985). Following them we represent the measured abundance ratio of two species N_i/N_j in a given event as a power-law in <Q/M>:

$$N_i/N_j = (S_i/S_j)[\langle Q/M\rangle_i/\langle Q/M\rangle_j]^{\gamma}$$

Where S_i/S_j is the coronal abundance ratio, and the index γ varies from at least – 10 to +5 (Garrard and Stone, 1994, Leske et al. 1999b). If the $^{22}Ne/^{20}Ne$ variations result from varying degrees of Q/M-dependent fractionation, elemental abundance enhancements should be correlated with $^{22}Ne/^{20}Ne$. In this paper we test the hypothesis that the elemental and isotopic variations result from the same Q/M-dependent process.

2 Solar Particle Data:

The nine solar events considered here were the largest observed by the Solar Isotope Spectrometer (SIS) on ACE during the period from launch (8/25/97) to the spring of 1999. The elemental and isotopic composition of these events has been reported by Cohen et al. (1999b) and Leske et al. (1999b). We can expect the $^{22}Ne/^{20}Ne$ variations to be correlated with variations in the abundances of neighboring elements if we consider two elements that have <Q/M> ratios that differ in the same manner under a broad range of conditions. For example, the mean charge-to-mass ratio for Fe is less than that for oxygen at all temperatures, even when these ions are fully stripped, and variations in ^{22}Ne/^{20}Ne are indeed correlated with those of Fe/O in these events (see Leske et al. 1999b). However, Fe charge states are very sensitive to temperature, and the mean Fe charge state is known to vary by as much as a factor of two with energy in a given event, and also to vary from event to event (e.g., Oetliker et al. 1997, Mazur et al. 1999, Moebius et al. 1999). As a result, the behavior of this correlation is difficult to predict. In addition, it may be more meaningful to compare the Ne isotope variations with those of elements having similar <Q/M> values.

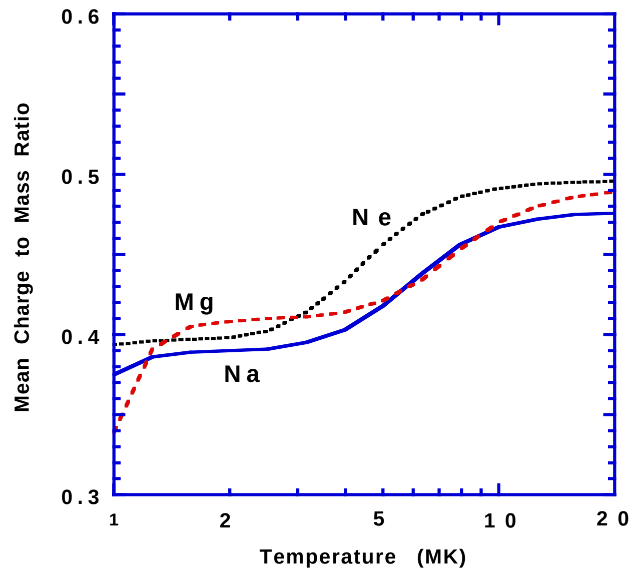

Figure 1: Mean Q/M ratios as a function of temperature based on the calculations of Arnaud and Rothenflug (1985).

Although there are no available high-energy measurements of SEP charge states for most of these events, Arnaud and Rothenflug (1985) have calculated charge-state distributions for a number of elements in thermal equilibrium over a range of temperatures. Figure 1 shows the calculated mean charge states of Ne, Na, and Mg (Z = 10, 11, and 12) as a function of temperature, assuming isotope abundances given in Anders and Grevesse (1989). Over the temperature range from ~1.5 to 4 MK the mean charge states of Na and Mg do not vary significantly from +9 and +10, respectively, because of their He-like electron configurations. Thus, the abundance of ^{23}Na

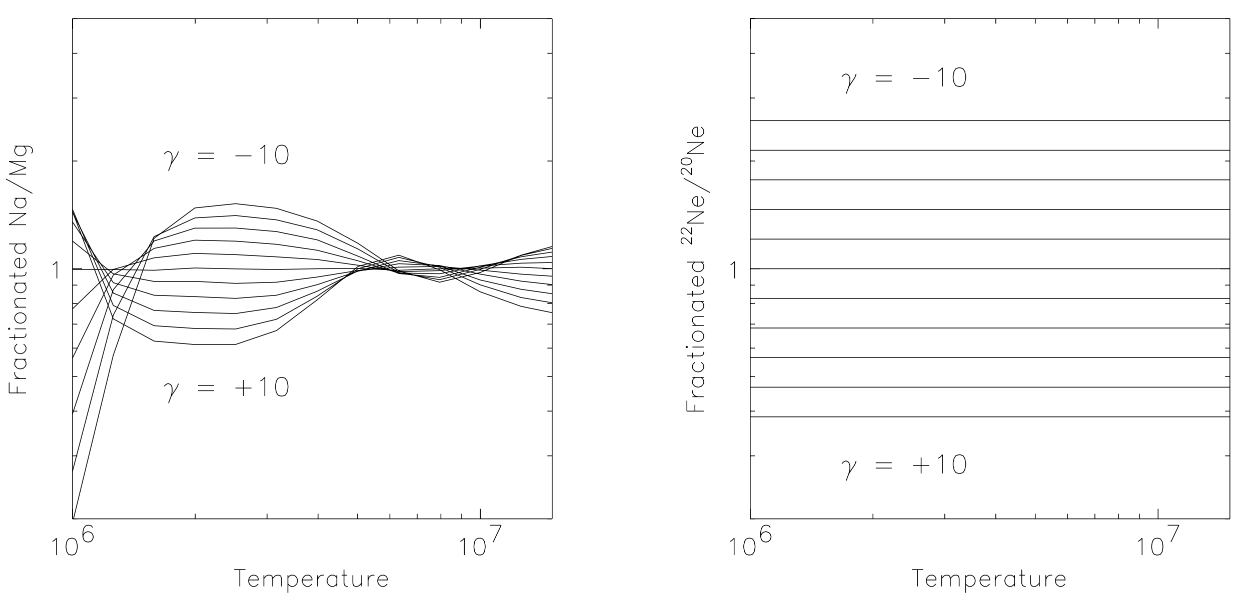

Figure 2: (left) Expected Na/Mg ratio vs. source temperature taking into account a fractionation process assumed to be a power-law in Q/M, with index γ. (right) Same as above, but for ^{22}Ne/^{20}Ne.

(Q/M = 0.39) relative to Mg (mean Q/M = 0.41 taking into account the isotopic composition) should be correlated with ^{22}Ne/^{20}Ne (note that ^{23}Na is neutron rich, as is ^{22}Ne).

If all charge states are affected by the same Q/M-dependent fractionation process, we can calculate the expected abundances for each charge state of the various isotopes of Ne, Na, and Mg. Figure 2 shows the expected ^{22}Ne/^{20}Ne and Na/Mg ratios as a function of temperature for power-law fractionation indices ranging from –10 to +10. Note that because ^{22}Ne and ^{20}Ne have the same charge state distribution, the expected ^{22}Ne/^{20}Ne ratio depends only on γ, and not on temperature. From Figure 2 it is clear that the ^{22}Ne/^{20}Ne and Na/Mg ratios should be strongly correlated for 1.5<=T<=4 MK, but anticorrelated (or perhaps weakly correlated for temperatures outside this range. There is also a region with T > 10 MK (where the ions become fully stripped) where a positive correlation is also expected with a somewhat different slope.

The comparison in Figure 3 illustrates that the data for these nine events show a correlation which agrees reasonably well with that expected for temperatures of ~1.5 to 4 MK, assuming that all charge states are enhanced by the same Q/M-dependent mechanism. There is no strong evidence that either the elemental or isotopic composition of the source material varies significantly from event to event. Although the overall agreement would improve if the coronal Na/Mg ratio were greater or the ^{22}Ne/^{20}Ne ratio less than the expected values, the observations are consistent with the assumption of a common Q/M-dependent fractionation process affecting both elemental and isotopic enhancements. It remains for theoretical models to identify appropriate acceleration/transport mechanisms that might lead to this fractionation.

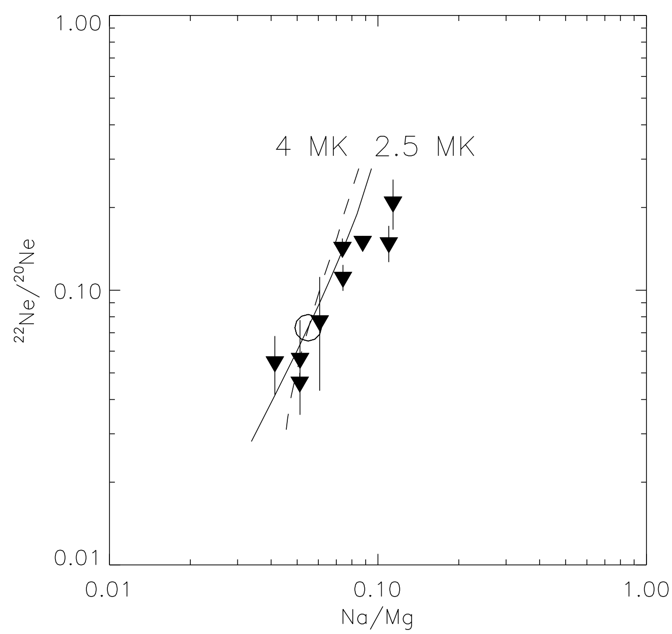

Figure 3: Observed correlation of the ^{22}Ne/^{20}Ne vs. Na/Mg ratios for nine large SEP events from 11/97 to 11/98. The curves are derived from Figure 2, assuming a fractionation process that is a power law in Q/M. The circle indicates the photospheric Na/Mg ratio (Grevesse and Sauval, 1998) and solar wind ^{22}Ne/^{20}Ne ratio (Geiss et al. 1972).

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