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High energy ionic charge state composition in large solar energetic particle events

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Abstract. Measurements of ionic charge states in solar energetic particle (SEP) events have been made at relatively high energies (> 15 MeV/nucleon) with the Mass Spectrometer Telescope (MAST) on board the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite using the Earth's magnetic field as a particle rigidity filter. We have examined the largest SEP events of solar cycle 23 and determined ionic charge states of Fe and other elements in several of these events. The mean charge state of Fe is often considerably higher (~ 20) in impulsive SEP events than in gradual events (~ 15). Surprisingly, in several cases, relatively high charge states of around 20 were found for Fe in very large events which are most likely gradual. Further, our measurements also show that Si in these events is not necessarily in thermal equilibrium with other elements.

1 Introduction

Solar energetic particle (SEP) events are usually classified into gradual and impulsive events (Reames, 1995a). Earlier studies found ionic charge states, Q, in gradual events to be generally consistent with those expected for a plasma of ~ 2 MK, with a mean Q for iron of ~ 15 at ~ 1 MeV/nucleon and with little event-to-event variability (Luhn et al., 1985). In a sum of 22 impulsive events, a higher mean charge state of ~ 20 was found for Fe (Luhn et al., 1987), suggesting an origin in hotter, $\sim 10^7$ K flare plasma or indicating that considerable stripping took place.

The Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite has successfully used the Earth's magnetic field as a particle rigidity filter at energies as high as ~ 70 MeV/nucleon (Leske et al., 1995). This approach can be used at lower energies (Mason et al., 1995; Oetliker et al., 1997; Mazur et al., 1999) for cross-calibration with direct measurements (Möbius et al., 1999). In addition to event-

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to-event variability, these measurements have shown that Q may depend on energy, which was confirmed by direct measurements at lower energies (Möbius et al., 1999).

The MAST instrument was launched in July 1992 on the SAMPEX spacecraft into a 520×670 km 82° inclination Earth orbit. MAST employs a silicon solid-state detector telescope with a collecting power of ~ 11 cm^{2}sr and uses the dE/dx versus residual energy technique to measure the nuclear charge, Z, mass, M, and total kinetic energy, E, for particles with energies of ~ 15 to ~ 150 MeV/nucleon (Cook et al., 1993; Leske et al., 2001a).

2 Analysis

We have examined MAST data from large SEP events from 10/30/92, 11/2/92, 11/6/97, 8/25/98, 9/30/98, 11/14/98, and 7/14/00 ("Bastille Day"). The 1992 events occurred during the declining phase of solar cycle 22, while the remainder of the events were in solar cycle 23.
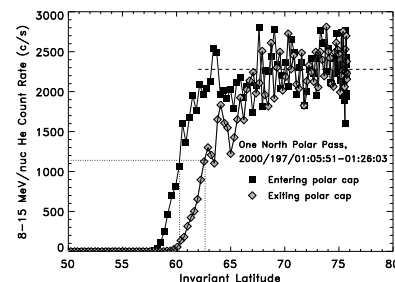

Fig. 1. The count rate of 8-15 MeV/nucleon He measured by MAST versus invariant latitude for one north polar pass on 15 July 2000.

During the near-polar Earth orbit of SAMPEX, MAST detects the geomagnetic cutoff of abundant charged particles as the spacecraft passes from high invariant latitude to low invariant latitude, or vice-versa, as shown in Figure 1 for 8-15
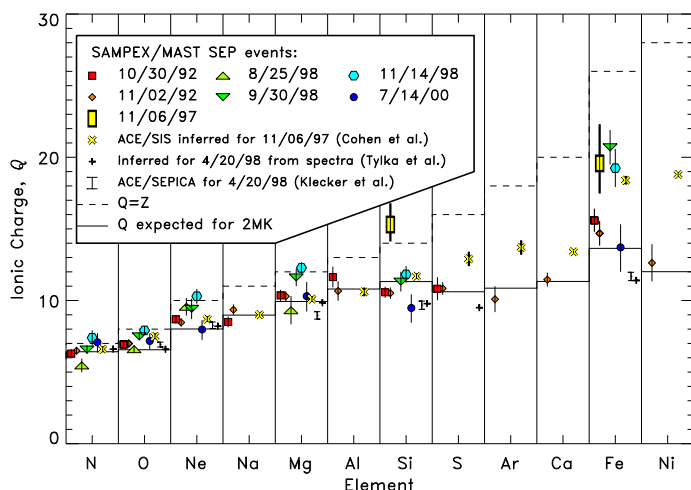
Fig. 2. Charge states determined by MAST in SEP events in 1992 (Leske et al. (2001a), and references therein) compared with those expected in a 2 MK plasma (solid horizontal lines) (Arnaud and Rothenflug, 1985; Arnaud and Raymond, 1992). Charge states deduced in the 6 November 1997 event are also shown (Cohen et al., 1999b), as well as charge states directly measured at lower energies (Klecker et al., 1999) and deduced from the spectral shape at higher energies (Tylka et al., 2000) in the 20 April 1998 event.

MeV/nuc He. Invariant latitude, Λ, is the magnetic latitude at which the field line intersects the Earth's surface and is related to the magnetic L shell by $\cos^2 \Lambda = 1/L$; see, e.g., Roederer (1970). Cutoff invariant latitude, Λ_C, is defined as the invariant latitude at which the count rate drops to half its average value above $70°$. Cutoff magnetic rigidity (momentum per unit charge), R_C, should be linearly related to $\cos^4 \Lambda_C$ (e.g., Smart et al., 1999). Given measurements of the cutoff latitude and kinetic energy, E, for a given species, one can therefore solve for Q.

Figure 1 also demonstrates the dynamic nature of Λ_C, which can vary by several degrees on timescales of less than one orbit, during periods of high geomagnetic activity. Further, heavy ions often arrive earlier and disappear sooner than lighter ions in SEP events, so our analysis normalizes for arrival time, in addition to livetime and duration at invariant latitude bins.

Further details of the analysis approach may be found in Leske et al. (1995, 1996, 2001a); Mason et al. (1995); Mazur et al. (1999); Oetliker et al. (1997).

3 Results

Charge states obtained by MAST in all of the SEP events studied to date are shown in Figure 2. The uncertainties are dominated by uncertainties in the derived cutoff-rigidity relations and might be reduced through further analysis. Except for a slightly low value for Q(Si), the charge states for the Bastille Day event are similar to those of the 1992 events.

A variety of other measurements of Q in gradual events obtained using other techniques are also shown Figure 2. Charge states from ACE/SIS (Cohen et al., 1999b) were deduced assuming the elemental and isotopic fractionation observed in the 6 November 1997 SEP event both scale as the same power law in Q/M. While the relatively high Q(Fe) value obtained from ACE/SIS agrees well with the MAST re-

sult in the same event, the Si charge states are very different. Other SAMPEX measurements in this event find Q(Si)~ 13 at ~ 2.5 MeV/nucleon and increasing with energy up to that point (Mazur et al., 1999), apparently more consistent with the MAST value than with the value of 11.7 ± 0.2 deduced by Cohen et al. (1999b) at 12–60 MeV/nucleon. This may indicate systematic differences between the two approaches that are unaccounted for or additional stripping of Si after elemental and isotopic fractionation.
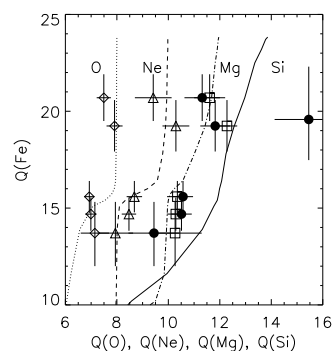

Fig. 3. Q(Fe) vs Q for O (open diamonds, dotted line), Ne (open triangles, dashed line), Mg (open squares, dot-dashed line), and Si (solid circle, solid line) from MAST data. Lines are calculated for mean charge states at thermal equilibrium (Arnaud and Rothenflug, 1985; Arnaud and Raymond, 1992).

For most elements, the measured charge states are often in reasonable agreement with those expected from equilibrium calculations of collisional ionization in a 2 MK plasma (Arnaud and Rothenflug, 1985; Arnaud and Raymond, 1992), a temperature typical of the solar corona. For the MAST 1997 and 1998 events shown, however, the high charge states of ~ 20 for Fe either require a higher temperature of ~ 10 MK
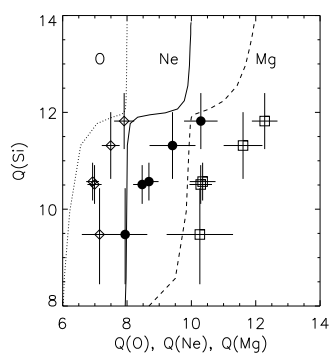
Fig. 4. MAST measurements of Q(Si) vs Q for O (open diamonds, dotted line), Ne (solid circle, solid line), and Mg (open squares, dashed line) from MAST data. Lines are calculated for mean charge states at thermal equilibrium (Arnaud and Rothenflug, 1985; Arnaud and Raymond, 1992).

or may suggest that additional stripping occurs during acceleration or transport (Barghouty and Mewaldt, 2000; Reames et al., 1999).

For the events in this study, mean charge states in MAST data for O, Ne, Mg, and Fe together are in good agreement with thermal equilibrium calculations over the range ~ 2–10 MK, as shown in Figure 3. The agreement with thermal equilibrium over this temperature range appears qualitatively as good as or better than some measurements for the same elements in the lower energy range measured by ACE SEPICA (Möbius et al., 2000). At Q(Fe) values near 20, the MAST results are in even tighter agreement with fully stripped ionic charge states of O, Ne, and Mg than the ACE SEPICA results, although MAST data in Figure 3 represent only two events. It is possible that the geomagnetic rigidity filter technique tends to result in correlations of high charge states between different elements. With uncertainty in the cutoff latitude to rigidity relationship (e.g. Shea and Smart (1983), Smart et al. (1999), Ogliore et al. (2001)), it is important to note that the cutoff latitude to rigidity relationship will have a strong effect on Q(Fe) measurement results.

A comparison of Q(Fe) and Q(Si) in Figure 3 shows little or no agreement with thermal equilibrium. Unlike O, Ne, and Mg, Si is apparently not fully-stripped for high values of Q(Fe). The comparison of Q(Si) vs. charge states of O, Ne, and Mg in Figure 4 further implies that the Si charge state is ~ 1 electron charge lower than that required of thermal equilibrium, assuming that Si and other elements in these SEP events originate at equal temperatures. The assumption of equal temperatures may be incorrect, however. Mean charge state measurements for Si and Mg as far back as the work of Luhn et al. (1985), for example, corresponded to temperatures which differed by ~ 5 MK from each other.

At lower energies of ~ 1 MeV/nucleon, a good correlation has been reported between Q(Fe) and the Fe/O ratio, with higher Q corresponding to enhanced Fe/O (Möbius
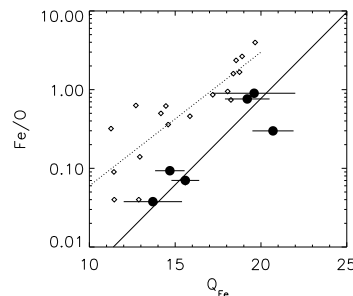

Fig. 5. Fe/O vs Q(Fe) for MAST data (closed circles; Fe/O ratios from Cohen et al. (1999a); Williams (1998); charge states from Leske et al. (2001a) and references therein) and ACE SEPICA and ULEIS data (open diamonds, error bars removed; Möbius et al. (2000)). The solid line is a fit to the MAST data, and upper dotted line is the fit to the SEPICA and ULEIS data.

et al., 2000). A similar trend for higher energy Fe studied by MAST is evident here, as shown in Figure 5 using the Fe/O ratio (for most of the events) obtained by ACE/SIS (Cohen et al., 1999a). Figure 6 demonstrates the same general trend for a variety of other elements. In Figure 5, it appears that for a given Fe/O value, Q(Fe) at MAST energies is generally higher than the value at low energies. This may suggest that an increase in the Fe charge state with energy is fairly common, as has been measured in at least two events (Möbius et al., 1999; Oetliker et al., 1997; Mazur et al., 1999).

It is unclear whether the correlation of composition and charge states is due to an admixture of impulsive SEP material into these otherwise gradual events (Mason et al., 1999), an origin of the material in hotter regions of the corona, or fractionation or charge-changing processes during acceleration or transport. The Q/M-dependent fractionation process that affects both elemental and isotopic abundances (e.g., Leske et al., 2001b) would not produce this correlation from material with a broad distribution of Fe charge states. If it
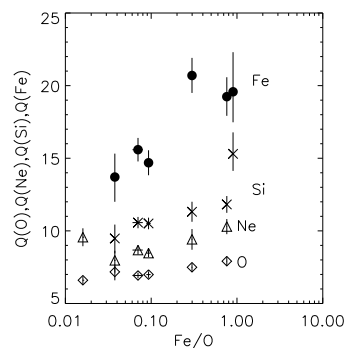

Fig. 6. Q for O, Ne, Si, and Fe, from MAST data only (Leske et al. (2001a) and references therein), vs Fe/O (Cohen et al., 1999a; Williams, 1998), for the gradual SEP events in this study.

Table 1. Mean Q for Fe-poor and Fe-rich gradual events from MAST

Element	avg Q, low Fe/O[a]	avg Q, high Fe/O[b]
N	6.36 ± 0.15	6.79 ± 0.27
O	6.90 ± 0.13	7.68 ± 0.21
Ne	8.63 ± 0.19	9.99 ± 0.42
Mg	10.26 ± 0.24	12.07 ± 0.33
Si	10.47 ± 0.27	$(11.98 \pm 0.42)^c$
Fe	15.02 ± 0.56	19.97 ± 0.82

(a) Average of events with Fe/O< 0.134, (b) Average of events with Fe/O> 0.134, (c) Average omitting the 11/6/97 event is 11.61 ± 0.44.

did, then when Fe/O is enhanced, indicating enhancements of elements with lower Q/M, the lower Q(Fe) should also be enhanced, opposite to what is observed.

If we divide the events according to whether the high energy Fe/O ratio is depleted or enhanced relative to the coronal value of 0.134 (Reames, 1995b) and calculate the average Q for each element in each of these two cases, we obtain the values given in Table 1. Because Q(Si) in the 11/6/97 event is so different from that in the other two Fe-rich events, we list values in Table 1 both with and without this event included in the average. Both values are significantly higher than the average Q(Si) in the Fe-poor events. In fact, for all 6 measured elements from N to Fe, the mean Q is significantly higher for the Fe-rich events, being some 5 charge units higher at Fe and essentially consistent with fully stripped for all elements up through Mg. The Q values for high Fe/O are very similar to those deduced indirectly by ACE/SIS in 4 Fe-rich gradual events (Cohen et al., 1999a).

4   Summary

Measurements from SAMPEX have uncovered unexpected behavior in gradual SEP event charge states. For most elements in most SEP events, charge states are consistent with a 2 MK plasma. Correlations between charge states and Fe/O ratio, reported by other experiments, are also seen by MAST. However, in some SEP events which would previously have been defined as gradual events, the charge states of Fe are more consistent with previous definitions of impulsive events. Furthermore, while charge states of O, Ne, Mg, and Fe are consistent with equal temperatures during each event, charge states of Si imply temperatures several MK lower than the temperatures implied by the charge states of the other elements.

The analysis of additional large events detected by MAST, namely the 9 November 2000 event and several large events in March and April of 2001, is underway and will be reported at the conference. Together with ongoing composition measurements from ACE, Wind, and other spacecraft, these new data offer the hope of revealing new details of the fractionation, acceleration, and transport of solar energetic particles.

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