High Energy Ionic Charge State Composition In Recent Large Solar Energetic Particle Events

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Abstract

The ionic charge states of solar energetic particles (SEPs) provide information on the temperature of source materials and on conditions during acceleration and transport. SAMPEX/MAST measures mean ionic charge states at > 15 MeV/nuc using the geomagnetic rigidity filter technique. Charge state measurements by MAST for gradual SEP events suggest a continuum of charge states correlated with abundance ratios for a variety of elements, similar to what is observed at lower energies. In cases where lower energy measurements are also available, the combined measurements indicate energy dependent charge states. We have completed ionic charge state measurements for 17 SEP events from solar cycle 23. We discuss the implications of our results.

1. Introduction

Ionic charge states of solar energetic particles (SEPs) depend upon the source material temperature and upon acceleration and transport conditions. SEP events are usually classified as either gradual events related to coronal mass ejections (CMEs) or impulsive, flare-related events [11]. Early measurements of iron ionic charge states at ∼1 MeV/nuc yielded Q(Fe)∼20 for impulsive events and Q(Fe)∼15 for gradual events (e.g. [6,8]). More recent measurements have yielded a continuum of ionic charge states for a variety of elements which vary from event to event, which appear to correlate with elemental abundances (e.g. Ne/O, Fe/O), and which show varying degrees of energy dependence (e.g. [7,10]). These measurements suggest a continuum of conditions involving SEP events and an overlap of some characteristics of gradual and impulsive events.

2. Measurements

The MAST instrument on SAMPEX is a silicon solid state detector telescope which identifies elements with charges $Z = 2 - 28$ over an energy range

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from ~ 10 MeV/nuc to ≥ 100 MeV/nuc using the ΔE vs. residual E technique. SAMPEX/MAST measures SEP ionic charge states using the geomagnetic rigidity filter technique, which has been described in detail in [5,6,7]. The polar orbit of SAMPEX allows MAST to detect the geomagnetic cutoff latitude of abundant ions such as $8-15$ MeV/nuc He during large SEP events. Time dependence in the cutoff latitude of these abundant ions can be used to correct time dependent variations in the cutoffs of less abundant, heavier ions, allowing for the determination of an average cutoff latitude for these less abundant ions over the duration of an SEP event. Assuming charge states of Q(He)=2 and Q(C)=$5.7-6$, measurements of He and C cutoffs are used to calibrate a relationship between geomagnetic cutoff and rigidity [12]. From this calibration and measurements of the time-dependence corrected cutoffs of heavier ions, the mean ionic charge states of heavier ions can be determined.

3. Results

Since SAMPEX was launched in July 1992, MAST has measured geomagnetic cutoffs and ionic charge states for 17 large SEP events from October 1992 to April 2002. The SEP events in the present analysis had onset dates of 10/30/92, 11/3/92, 11/6/97, 8/25/98, 9/30/98, 11/14/98, 7/14/00, 11/8/00, 4/3/01, 4/10/01, 4/15/01, 8/15/01, 9/24/01, 11/4/01, 11/23/01, 12/26/01, and 4/21/02. Results for the 7 SEP events from October 1992 to July 2000 have been published previously [5,6,7]. The measurements for the 10 SEP events from November 2000 to April 2002 are new results.

Figure 1 shows mean ionic charge states for selected elements (O, Si, and Fe) vs. Fe/O, and Figure 2 shows mean ionic charge states for Ne, Si, and Fe vs. Ne/O. For the events of 1992, abundance ratios are from [14], while the rest of the ratios are from ACE/SIS data [3]. The data show apparent correlation between ionic charge states and Fe/O, most pronounced in Q(Fe) because of the wider range of values available to Q(Fe) than for other elements. The Q(Fe) values are clustered into low Q and high Q groups, but other elements (such as Si and O in Figure 1) exhibit continua of mean ionic charge states. The apparent clustering of Fe ionic charge states may be a result of the lower number of available Q(Fe) measurements. Ionic charge states are also correlated with Ne/O, with the exception of Q(Fe).

The Fe/O abundance ratio is of interest because measured Fe/O ratios for gradual SEP events average around the coronal average of 0.134, while impulsive events have been measured with Fe/O ratios to well over ~ 10 times the coronal average, with considerable overlap between the gradual and impulsive Fe/O values [11]. Similarly, Ne/O ratios for gradual events cluster around the coronal value of 0.152, while impulsive events have Ne/O ratios $\sim 2-10$ times the coronal value, again with considerable overlap between gradual and impulsive Ne/O ratios [11].

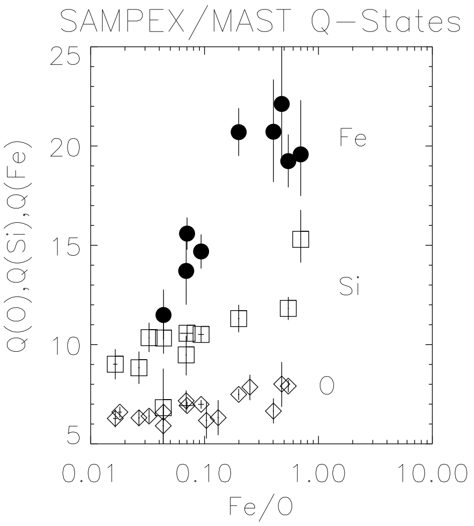

Fig. 1. Mean charge states of O, Si, and Fe vs. Fe/O ratio. Charge states are from [5,6,7] and this work. Fe/O ratios are from [3,14].

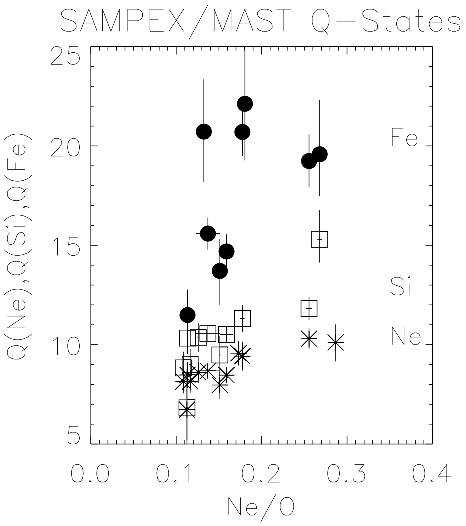

Fig. 2. Mean charge states of Ne, Si, and Fe vs. Ne/O ratio. Charge states are from [5,6,7] and this work. Ne/O ratios are from [3,14].

The high Q(Fe) events measured by SAMPEX in this analysis have Fe/O ratios within the overlap of values for gradual and impulsive events. Three of the events with Ne/O ratios below the coronal average (0.152) have Q(Fe) values well within the range typical of impulsive events.

Mason et al. (1999) [9] have suggested that many SEP events may include a component of remnant suprathermal material from impulsive events based on ^{3}He abundance enhancements. However, our available Q(Fe) measurements and Fe/O ratios alone are not conclusive evidence for or against their hypothesis.

Alternatively, Cane et al. (2003) [1] have suggested that some SEP events have a flare component concurrent with a shock-accelerated component, in contrast with the explanation which suggests flare-related material is produced before the SEP event [9]. They point out that most of the SEP events with impulsive signatures which they have studied have western solar source regions consistent with flares magnetically well-connected to the Earth. Figure 3 shows a plot of mean ionic charge states measured by MAST vs. west solar longitude of the associated flares as obtained from NOAA. High Q(Fe) values cluster at well-connected west longitudes, consistent with the Cane et al. explanation. Correlation with other charge states is less obvious.

Figure 4 compares the Q(Fe) vs. Fe/O correlation observed for SAMPEX/MAST data with a similar correlation observed in ACE/SEPICA and ULEIS data for gradual and impulsive events [10]. In both cases, correlation is observed, but for any given range of available Fe/O values, the higher energy MAST measurements report higher Q(Fe) than the 0.18 – 0.44 MeV/nuc SEPICA Q(Fe)

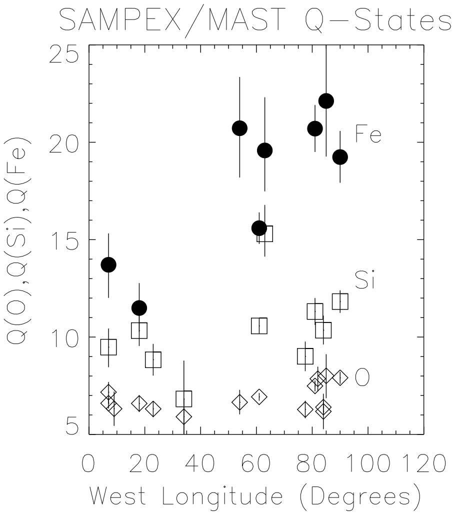

Fig. 3. Measured charge states of O, Si, and Fe vs. west solar longitude. Charge states are from [5,6,7] and this work. Solar source longitudes are from NOAA data.

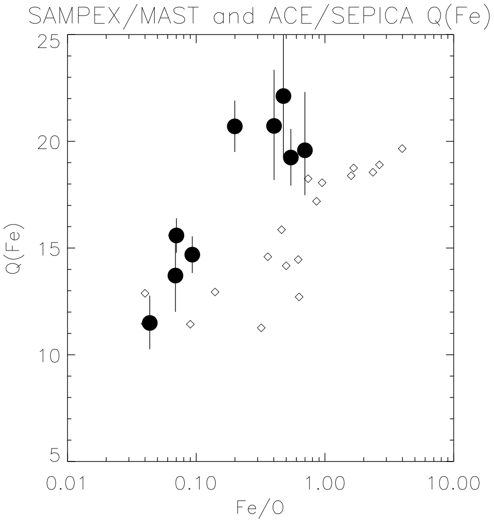

Fig. 4. Q(Fe) vs. Fe/O for MAST data (solid circles) and ACE SEPICA and ULEIS data (open diamonds, error bars removed). ACE charge states are from [10].

measurements. This energy dependence in Q(Fe) might be explained in terms of different acceleration and transport models (e.g. [1]) or by a varying mixture of impulsive flare and coronal-like material (e.g. [13]).

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4. References

1. Barghouty, A.F. and Mewaldt, R.A. 2001, in AIP Conf. Proc. 528, 71.
2. Cane, H.V. et al. 2003, Geophys. Res. Lett., in press.
3. Cohen, C.M.S. 2003, private communication.
4. Cook, W.R. et al. 1993, IEEE Trans. Geosci. Remote Sensing, 31, 557.
5. Labrador, A.W. et al. 2001, Proc. 27th ICRC, Hamburg, 8, 3149.
6. Leske, R.A. et al. 1995, ApJ, 452, L149.
7. Leske, R.A. et al. 2001, in AIP Conf. Proc. 598, 171.
8. Luhn, A. et al. 1987, ApJ, 317, 951.
9. Mason, G.A. et al. 1999, ApJ, 525, L133.
10. Moebius, E. et al. 2000, in AIP Conf. Proc. 528, 131.
11. Reames, D.V. 1999, Space Sci. Rev., 90, 413.
12. Smart, D.F. et al. 1999, Proc. 26th ICRC, Salt Lake City, 7, 337.
13. Tylka, A.J. et al. 2001, ApJ, 558, L59.
14. Williams, D.L. 1998, Ph.D. Thesis, Caltech, Pasadena, CA 91125.