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High Energy Ionic Charge State Composition in the October/November 2003 and January 20, 2005 SEP Events

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The ionic charge states of solar energetic particles (SEPs) probe source-material temperatures and acceleration and transport conditions. The MAST instrument on SAMPEX measures SEP ionic charge states at energies greater than ~15 MeV/nuc and at iron energies up to ~90 MeV/nuc using the geomagnetic filter technique. Charge state measurements for large gradual SEP events by MAST and by other experiments suggest that event-to-event variations in the mean charge states of abundant elements are correlated with abundance ratios (e.g. Fe/O). We present charge state measurements for the October/November 2003 events that suggest different source material temperatures for these events. We also present charge state measurements for the January 20, 2005 event, which contrasts with the previously demonstrated Q(Fe) vs. Fe/O correlation. In this event solar and SEP data indicate that the first high-energy particles left the Sun when the CME shock was ~1.5 solar radii above the solar surface. At this altitude charge-equilibration calculations and the observed mean charge state of +12 for Fe imply that <90 seconds were available to accelerate and release the particles. These observations therefore present a serious challenge to SEP acceleration models.

1. Introduction

Solar energetic particle events are usually separated into two categories, gradual and impulsive events [1]. Gradual events are characterized by coronal elemental composition (e.g. Fe/O ~ 0.134) and low ionic charge states (e.g. Q(Fe)<16) corresponding to coronal plasma temperatures. Gradual evnts are associated with coronal mass ejections (CMEs). Impulsive events are characterized by higher He-3 and heavy element relative abundances (e.g. Fe/O several times coronal average) and higher ionic charge states (e.g. Q(Fe)>18). Impulsive events are associated with flares.

Early measurements of the mean charge state of iron (Q(Fe)) yielded ~20 for flare–related events, consistent with 10^7K flare plasmas, while early measurements of Q(Fe) for CME–related events were around ~15, consistent with ~2 MK plasmas typical of the corona [2-6]. Recent measurements by instruments aboard the Advanced Composition Explorer (ACE) and the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) have yielded mean ionic charge states correlated, event to event, with elemental abundances (e.g. Ne/O, Fe/O) [7-8]. These measurements suggest either a continuum of SEP events or an overlap between classes of SEP events.

Measurements by the Mass Spectrometer Telescope (MAST), aboard the Solar, Anomalous, Magnetospheric Particle Explorer (SAMPEX) employ a geomagnetic rigidity filter technique to measure average ionic charge states for large SEP events [4]. MAST can measure C up to ~40 MeV/nucleon and Fe up to ~100 MeV/nucleon. The energy range of MAST and the geomagnetic filter rigidity technique together extend the energy range for ionic charge states well above that available to electrostatic deflection measurements.

SAMPEX was launched on July 1, 1992, into an 82° inclination orbit, with an altitude of 520-670 km, and at the time of this writing, it has been in continuous operation since launch.

2. Geomagnetic Rigidity Filter Method

Use of the geomagnetic filter technique by MAST has been described in detail [4], and the basic analysis technique is little changed in the current analysis. Ionic charge state measurements by MAST begin with measurement of cutoff invariant latitude Λ_C for He at 8-32 MeV/nuc using the MAST Z2 rate through the duration of the SEP event. The Z2 rate is corrected for livetime. Helium is selected because, for most of the duration of a large SEP event, this element is abundant enough for MAST to measure cutoff invariant latitude into and out of polar regions for each orbit of SAMPEX. Plots of livetime-corrected Z2 rate vs. invariant latitude for a single polar orbit show sharp cutoffs that can usually be fit with a straight line, and cutoff latitude is defined as the point on the line at half the Z2 rate of the near-polar average rate. For charge states analysis, the duration of an SEP event is generally the time during which Z2 cutoffs may be determined cleanly.

For rarer species (e.g. C, N, O, and Fe), the counts are not high enough to yield cutoff invariant latitude measurements for each polar pass. However, for each species and energy, the cutoff invariant latitude has been shown to exhibit time-dependent variation similar to that measured for Z2, assuming that the average ionic charge state for each species does not change radically over the duration of the event [8]. The Z2 cutoff time-dependence is used as a template to correct invariant latitudes for individual particles for the rarer species. Then, for each species and energy range, the individual particle counts for the duration of the SEP event are histogrammed versus corrected invariant latitude, yielding count vs. corrected invariant latitude profiles similar to the Z2 rate vs. invariant latitude profiles for individual polar passes. These histograms yield cutoff latitudes for the rarer species. If statistics are limited for a given species in a specific SEP event, a cutoff latitude and corresponding charge state may not be obtained for that species.

Calculations of cutoff invariant latitude for protons imply a linear relationship between cutoff magnetic rigidity, R_C, and $\cos^4\Lambda_C$ [9]. The linear relationship between R_C and $\cos^4\Lambda_C$ is calibrated by measurements of He and C energy and cutoff invariant latitudes, assuming Q(He)=2 and Q(C) between 5.7 and 6, and this relationship is extrapolated linearly to higher values of R_C and $\cos^4\Lambda_C$ appropriate for rarer, heavier species. Average ionic charge states for heavier species are then deduced from the calibrated linear relationship between R_C and $\cos^4\Lambda_C$ when cutoff measurements are available.

2. Discussion

Charge state measurements using SAMPEX/MAST data are shown in Figure 1 for the 28 October 2003, 29 October 2003, 2 November 2003, and 20 January 2005 events. The figure shows mean ionic charge state vs.

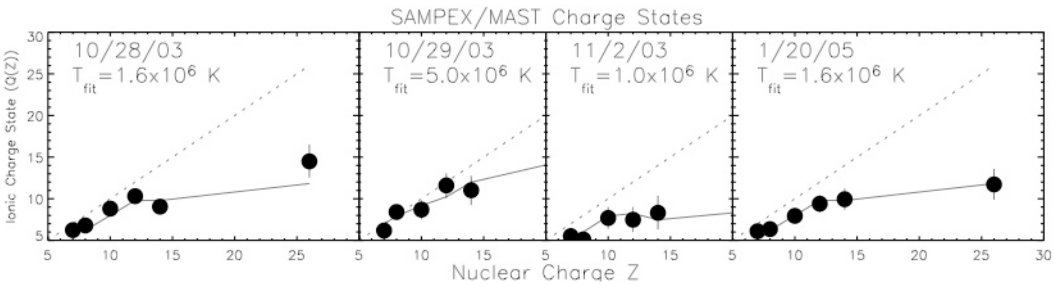

Figure 1: SAMPEX/MAST mean ionic charge state measurements vs. nuclear charge for the 28 Oct. 2003, 29 Oct. 2003, 2 Nov. 2003, and 20 Jan. 2005 SEP events. The dashed line is the Q(Z)=Z (fully-stripped) line, and the solid lines are fits to plasma temperature calculations.

nuclear charge state for N, O, Ne, Mg, Si, and Fe. Q(Fe) measurements are not available for the 29 Oct 2003 and 2 Nov 2003 events because of poor Fe statistics. Plasma temperature calculations, assuming thermal equilibrium conditions, are fitted via chisquare minimization to the charge state measurements [10].

The three 2003 SEP events were the three largest of a series of 5 large SEP events that occurred over a ten day period. Each of the events is associated with an X-class flare, a fast CME, and an interplanetary shock observable in particle data. Although the events are part of a series of events closely associated in time, the charge state measurements imply different source plasma temperatures. A difference in source material is shown in Figure 2, which shows ionic charge state measurements vs. Fe/O ratio. In this figure, the 28 Oct. and 2 Nov. 2003 events also show lower Fe/O ratios, compared to the 29 Oct. 2003 event.

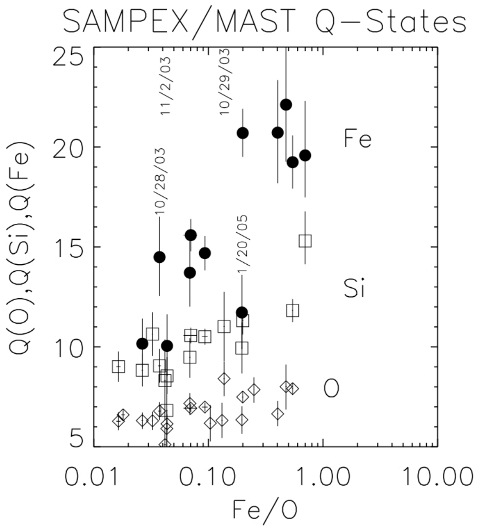

Figure 2: SAMPEX/MAST ionic charge state measurements vs. Fe/O ratio from ACE/SIS measurements [11]. For the two events of this paper with available Q(Fe) measurements, the Q(Fe) points are labeled. The two events without Q(Fe) measurements are labeled at their Fe/O ratio at the top of the plot.

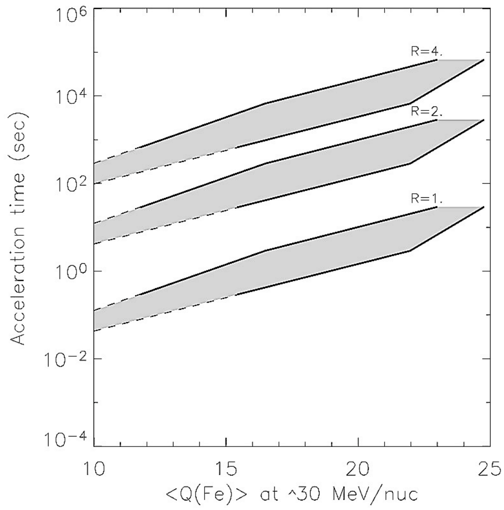

Figure 3: Acceleration time vs. Q(Fe) for various altitudes in solar radii (solar surface at R=1). Charge equilibration calculations for plasmas are by [12], combined with an electron density model by [13]. Lower bounds assume constant acceleration; upper bounds assume dE/dt proportional to E. Dashed lines extrapolate to Q(Fe)=10.

Figure 2 shows strong correlation between mean ionic charge states and the Fe/O ratio, as has been observed and commented upon before, e.g. [14]. Although the older distinction between gradual and impulsive events had Q(Fe)>18 and high Fe/O for impulsive events and Q(Fe)<16 and low Fe/O for gradual events, these observations suggest a possible continuum of charge states and Fe/O ratios for large, gradual SEP events. (A mean charge state continuum is more strongly suggested in Q(O) and Q(Si) than in Q(Fe), perhaps because more measurements are available for O and Si.) Possible explanations include a mixture of coronal and flare material in the high charge state events, either remnant flare material [15] or concurrent flare material accelerated in the event [16].

The 20 Jan. 2005 event is interesting in the figure because it appears to be an outlier to the charge state vs. Fe/O ratio correlation, with Q(Fe)=~12. In fact, the September 1998 SEP event (not labeled on the Figure) has an almost identical Fe/O ratio but an average iron charge state above 20. The 20 Jan. 2005 event was characterized by a large X7.1 flare followed within minutes by particles detected near Earth, and it was one of the largest ground level events (detected by neutron monitors) in the past 50 years.

Figure 3 shows calculations of acceleration time vs. Q(Fe) for various altitudes above the solar surface (in units of solar radius (Rs); solar surface is defined at R=1). The calculations combine charge equilibration calculations for Fe ions in hot plasmas with a model of electron density in the solar corona [12,13]. An iron charge state of ~12 is essentially coronal iron material with no further stripping. The calculations show that iron with a charge state of ~12 would have to be accelerated and leave the source region within ~10-30 seconds at R < 2 Rs (or <1 Rs above the solar surface), depending on acceleration rate. At R=4 (3 Rs above solar surface), the maximum acceleration times are ~200-750 seconds. For comparison, LASCO and other images imply that the CME shock front was ~1.5 solar radii above the surface when the first protons left the Sun [17], implying a maximum acceleration time of ~30-90 seconds under this model.

3. Conclusions

The charge state measurements, combined with abundance ratio measurements, provide an interesting and varied picture of the events of late 2003. The charge states alone imply varying source temperatures for these closely associated events. Otherwise, they reinforce the correlation between charge state measurements and abundance ratios observed with other events in the past solar cycle.

On the other hand, the 20 Jan. 2005 event provides some challenges to previous observations and models. The charge states and Fe/O ratio make it an outlier to the correlation observed for events of the past solar cycle. While the solar and SEP observations imply the particles were released when the shock was ~1.5 solar radii above the surface, the Q(Fe) measurement and charge-equilibration calculations allow a maximum acceleration time of <90 seconds at this altitude. Current shock acceleration models may be hard pressed to explain the high energies and hard spectra with such little time to accelerate.

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