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Charge States of Solar Energetic Particles Using the Geomagnetic Cutoff Technique: SAMPEX measurements in the 6 November 1997 Solar Particle Events

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Abstract

We report on the ionization states of ~0.5-50 MeV/nucleon ions in the 6 November 1997 solar particle event using instrumentation on the SAMPEX satellite and the geomagnetic cutoff technique. Using the geomagnetic cutoffs of ~10 MeV 4He and ~20 MeV protons, we infer the ionization states of ~0.5-50 MeV/nucleon C-Fe by measuring their latitude distributions. The geomagnetic cutoff method extends the measurement of ionization states beyond 10 MeV/nucleon, where charge state information is inaccessible with present electrostatic deflection techniques. In contrast to an increase of the Fe charge state observed above ~20 MeV/nucleon in events in late 1992, we find in the 6 November 1997 event that Si & Fe charge states increased dramatically across 0.5-50 MeV/nucleon. While the origin of this newly discovered energy dependence is unknown, such significant event to event variations of solar particle charge states should be considered in models of acceleration and transport processes.

1 Introduction

The most intense solar energetic particle (SEP) events observed at 1 AU are associated with coronal mass ejections, interplanetary shocks, and long-duration solar x-ray events. The time structure of SEP fluxes depends on the magnetic connection between the observer and the propagating shock and the strength of the shock. The similarity of the low-energy SEP composition to the solar wind (e.g. Mazur et al. 1993), the independence of SEP composition with x-ray flare longitude (Mason et al. 1984), and the rough consistency of SEP O-Fe ionization states with coronal temperatures near 2x106 K (e.g. Leske et al. 1995) also suggest that SEPs in large events originate at an interplanetary shock rather than at the site of an optical flare in the chromosphere.

Even though the overall observational picture supports interplanetary acceleration in CME-related events, recent measurements of SEP ionization states in large events suggest more complexity in how the acceleration process affects particles of different rigidity than indicated in the charge state survey by Luhn et al. [1985]. As the first large SEP events of solar cycle 23, the 4 & 6 November 1997 events provided not only an opportunity to study SEP composition and ionization states with new instrumentation on the ACE spacecraft but also the first opportunity since late 1992 to apply the geomagnetic cutoff technique to deduce ionization states with instrumentation on board the SAMPEX satellite. Here we report on the ionization states using the cutoff technique in the 6 November 1997 event. The technique allows us to extend the measurements of the ionization states beyond 10 MeV/nucleon; ion charge states at these high energies are inaccessible to direct measurements using present electrostatic deflection techniques. We find that in contrast to the October/November 1992 events, the charge states of Si & Fe in the 6 November 1997 event increased with increasing energy, even below 1 MeV/nucleon. Energy-dependent charge states, here at an energy a factor of ~20 below the increase observed in the late 1992 events, suggest that we need more measurements of SEP ionization states before we consider average charge states. The variability has implications not only for studies of the possible sources of the energetic particles, but also for how the acceleration process may affect particles with different rigidity.

2 Instrumentation

The observations presented here are from the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) spacecraft, launched into a 512 x 675 km, 82° inclination Earth orbit in July 1992. The spacecraft's low Earth orbit passes through the polar caps and lower latitudes where SEPs no longer have access because of their gyroradii. The measurement of these cutoff latitudes for each species and energy bin, done in ground-based processing, is the essence of the geomagnetic cutoff technique. Mason et al. [1995] and Leske et al. [1995] presented the ionization states of solar energetic particles in large events that occurred in late 1992 using this cutoff technique. The results presented here are from the first event to occur in 5 years with sufficient fluxes for measurements of the average particle cutoffs; this was also the first intense, long duration solar particle event of solar cycle 23.

3 Observations and Data Analysis

Figure 1 presents the time intensity profiles of 0.5 MeV/nucleon 16O and 19-28 MeV protons in early November 1997. Two X-class x-ray events occurred in the interval from 3 November to 11 November 1997, with related coronal mass ejections observed on the SOHO spacecraft and distinct injections of >10 MeV/nucleon ions observed with a number of instruments at 1 AU (Mason et al. 1998). The close timing of the two mass ejections, combined with the effects of particle velocity dispersion, lead to the complex profiles seen below a few MeV/nucleon.

The hatched interval from 0005UT on 7 November 1997 to 1156UT on 9 November 1997 indicates the time period we used for charge state determination with the geomagnetic cutoff technique. SAMPEX was spinning at 1 rpm prior to this interval, and was commanded to rotate once per orbit at 2310UT on 6 November 1997 in order to better measure the particle cutoff latitudes. The charge state interval ends at 1156UT on 9 November 1997 when the polar averaged rate of 19-28 MeV protons fell below 2 counts/sec; we required good statistical accuracy of this rate since we used it to correct for the time-dependent geomagnetic cutoff. Mobius et al. [1998] discuss the charge states observed over roughly the same time period with the SEPICA instrument on the ACE spacecraft.

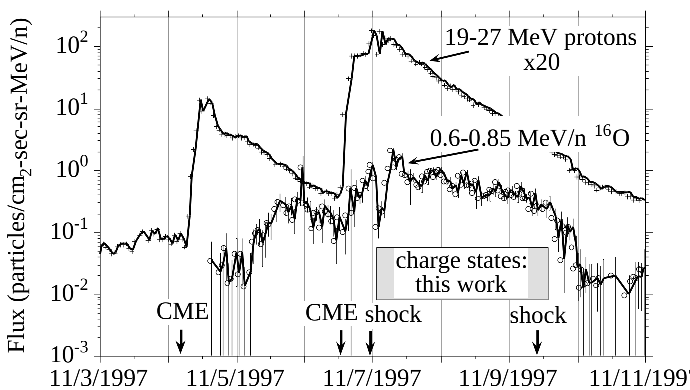

Figure 1. Time intensity profiles of 0.5 MeV/nucleon ^{16}O and 19-28 MeV protons in early November 1997.

For ions to arrive at the instantaneous latitude of SAMPEX they need to have sufficient magnetic rigidity (momentum per unit charge); the cutoff rigidity is ~0 GV over the magnetic poles, and increases to ~15 GV at the magnetic equator. We used SAMPEX to measure the minimum cutoff rigidity of the particles, as well as their mass and energy, in order to derive their charge states. Near 1 MeV/nucleon, it is necessary to measure the cutoff rigidities for particles of known charge states (e.g. H^{+1}) on an orbit-by-orbit basis, rather than to calculate cutoff rigidities with models of the Earth's magnetic field since present models do not accurately describe neither the low energy cutoffs nor their time dependences. As shown in Figure 2, the geomagnetic storm that commenced after the arrival of the interplanetary shock near 2200UT on 6 November 1997 suppressed the geomagnetic cutoffs by ~9°. The Dst index decreased as the ring current in the Earth's magnetosphere increased in intensity, and the cutoffs of low energy oxygen and the 19-28 MeV protons had similar trends. Such a suppression of the cutoffs of energetic ions during geomagnetic storms is complex and variable on the time scale of a SAMPEX orbit and therefore difficult to model. However, using SAMPEX we are able to measure and correct for the time-dependent cutoffs in the subsequent analysis of ionization states.

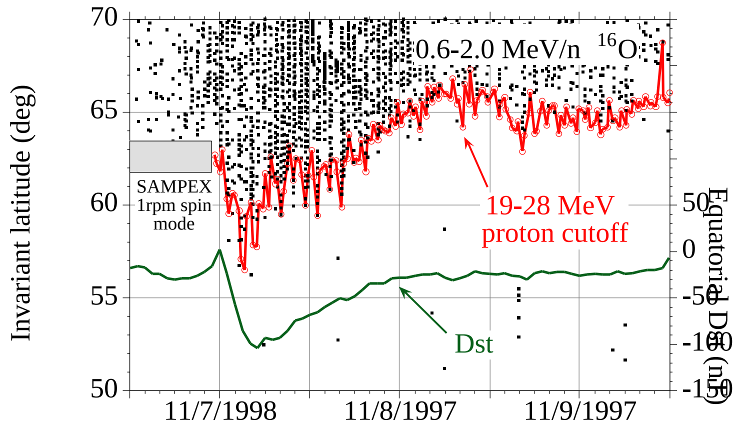

Figure 2. Time-dependent geomagnetic cutoffs during the 6 Nov. 1997 particle event.

Table 1. Ionization states in the 6 November 1997 particle event compared to previous measurements: ~0.5 - 2.5 MeV/nucleon.

Element	6 November 1997		Oct./Nov. 1992 [a]	Luhn et al. 1985 [b]
	0.5 - 1.25 MeV/n	1.25 - 2.5 MeV/n	0.5 - 2.5 MeV/n	~0.5 - 2.5 MeV/n
^{1}H	0.97 ± 0.51 [c]	1.02 ± 0.11 [c]	-	-
^{4}He	2.01 ± 0.46 [c]	2.01 ± 0.10 [c]	2.01 ± 0.11 [c]	-
^{12}C	5.82 ± 0.97	-	6.08 ± 0.32	5.70±0.29
^{14}N	-	5.53 ± 0.18	6.95 ± 0.58	6.37±0.32
^{16}O	5.83 ± 0.45	7.24 ± 0.38	7.61 ± 0.37	7.00±0.35
^{20}Ne	7.78 ± 0.47	-	9.56 ± 0.46	9.05±0.46
^{24}Mg	9.16 ± 1.38	9.61 ± 0.32	10.69 ± 0.55	10.70±0.54
^{28}Si [d]	8.09 ± 0.44	12.71 ± 0.54	10.83 ± 0.49	11.00±0.55
Fe (group)	12.54 ± 0.35	13.94 ± 0.34	11.12 ± 0.26	14.9±0.75

[a]Energy dependence seen only in Fe above ~20 MeV/n.
[b]Average of 12 events from Sept. 1978 - Sept. 1979.
[c]Normalization used in the geomagnetic cutoff technique.
[d]Si energy ranges: 0.4 - 1.25 MeV/n & 1.25 - 2.5 MeV/n.

Table 1 lists the average ionization states from ~ 0.5 - 2.5 MeV/nucleon in the 6 November 1997 event, in the October/November 1992 events also measured on SAMPEX (Mason et al. 1995; Leske et al. 1995; Oetliker et al. 1997), and ionization states measured in 1978-1979 with an electrostatic deflection instrument on ISEE-3 (Luhn et al. 1985). In contrast to October/November 1992 events and the ISEE-3 measurements, we find a significant energy dependence of the charge states of O, Si, & Fe near 1 MeV/nucleon in the 6 November 1997 event.

Figure 3 compares the charge states of Si & Fe during 6-9 November 1997 with those measured with the same geomagnetic cutoff technique in the October/November 1992 events. The dashed curves are not model fits to the data; we show them to better contrast the energy dependences. There were fewer measurements above 10 MeV/nucleon for 6-9 November 1997 because of reduced exposure to precipitating particles in the 1 rpm spin mode at the event's onset, lower MAST livetime, and expended gas in the SAMPEX/HILT sensor. Nevertheless, the charge states in these two events had greatly different trends with energy.

4 Discussion

The origin of the differences in ionization states of Figure 5 is not known; it may be the case that in the average used to derive the charge states, we combined an accelerated local solar wind component with higher energy ions accelerated nearer the sun. The different charge states seen above and below 10 MeV/nucleon may then be due to different source temperatures (flare vs. solar wind), or due to different acceleration efficiencies, or some combination thereof. The 6 November 1997 event had transitions in the Fe and O spectra near 1 MeV/nucleon, and a relatively high Fe abundance (Fe/O~ 1) above 10 MeV/nucleon (Mason et al. 1998); these features were not present in the Oct./Nov. 1992 events. It appears that both the charge states and spectral features may indicate different particle sources above and below 1 MeV/nucleon.

Through comparisons of SEP ionization states in more events observed simultaneously with ACE and SAMPEX, we hope to gain insight into the differences observed at low energies in the 6 November 1997 event as well as more insights into the locations of the SEP particle acceleration and the role of magnetic rigidity in the acceleration process.

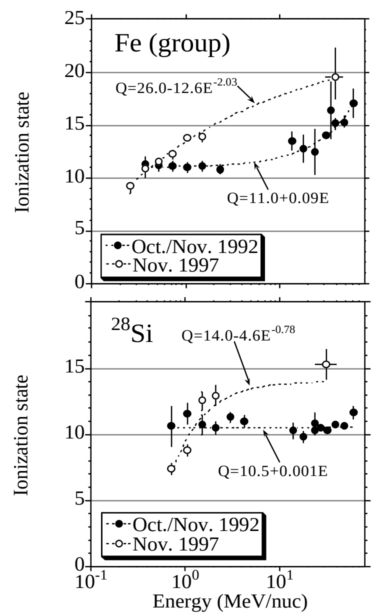

Figure 3. Ionization states versus energy in 2 events.

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