

Charge states of solar energetic particles using the geomagnetic cutoff technique: SAMPEX measurements in the 6 November 1997 solar particle event

J. E. Mazur¹, G. M. Mason^{2,3}, M. D. Looper¹, R. A. Leske⁴, and R. A. Mewaldt⁴

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.

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 (*e.g.* Reames 1997). 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 2×10^6 K (*e.g.* Leske *et al.* 1995; Ruffolo 1997) 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]. For example, in a report of ionization state measurements from ~0.5-60 MeV/nucleon observed in late 1992, Oetliker *et al.* [1997] found the charge state of Fe increased from ~11 near 1 MeV/nucleon to ~15 above 20 MeV/nucleon. Boberg *et al.* [1995] suggested that a charge state near 14 for ~200 MeV/nucleon Fe indicated that the source of the Fe may have been heated plasma in the sheath of the CME rather than the solar wind.

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 (Mason *et al.* 1998; Mobius *et al.* 1998; Cohen *et al.* 1998), 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.

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 (Baker *et al.* 1993). 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

¹Aerospace Corporation, Los Angeles, CA.

²Department of Physics, University of Maryland, College Park.

³Institute for Physical Science and Technology, University of Maryland.

⁴California Institute of Technology, Pasadena CA.

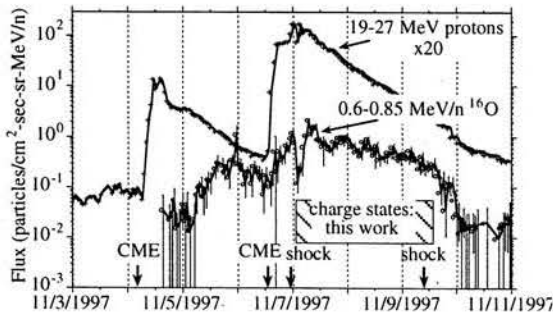


Figure 1. Time-intensity profiles of 19-27 MeV protons and 0.6-0.85 MeV/n ^{16}O during early November 1997. The protons show two distinct particle injections that occurred in coincidence with coronal mass ejections (CMEs) and x-ray events. The profiles of lower energy ions are less distinct due to velocity dispersion. The cross-hatched interval is the time period for SEP charge state analysis using SAMPEX.

was also the first intense, long duration solar particle event of solar cycle 23.

The ion composition measurements from ~ 0.5 - 5 MeV/nucleon are from the LICA sensor, a time-of-flight mass spectrometer with large geometry factor (~ 0.6 cm 2 sr) and excellent mass resolution (Mason *et al.* 1993). The higher energy composition measurements from ~ 20 to 50 MeV/nucleon are from the MAST sensor, a multiple dE vs E telescope (Cook *et al.* 1993a). We used the PET sensor (Cook *et al.* 1993b) to determine 19-28 MeV proton cutoff latitudes in order to correct for the time variations in the cutoff latitudes and to extend the cutoff versus rigidity calibration to higher rigidities.

Observations & Data Analysis

Figure 1 presents the time intensity profiles of 0.5 MeV/nucleon ^{16}O 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.

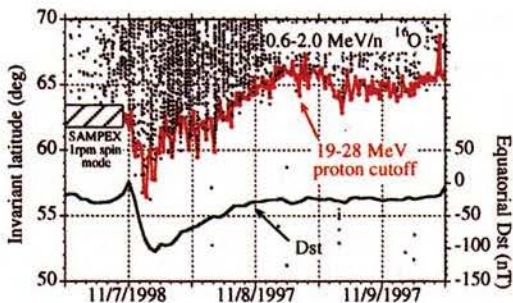


Figure 2. Time-dependent geomagnetic cutoffs during the 6 November 1997 SEP event. The red trace is the cutoff latitude for 19-27 MeV protons defined as the latitude at which the polar averaged count rate falls by 50%. The cutoffs of low energy ^{16}O ions (solid points) follow a similar time dependence, as does the Dst index.

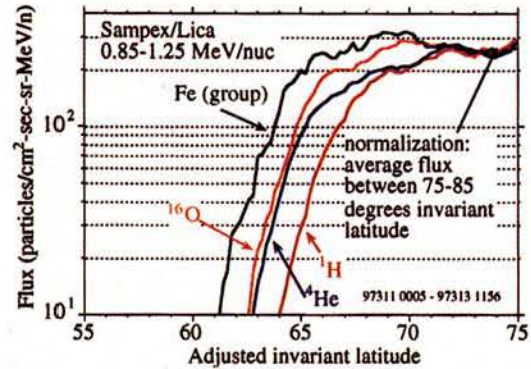


Figure 3. Adjusted latitude profiles of 0.85-1.25 MeV/n ions, averaged from 0005UT on 7 November 1997 to 1156UT on 9 November 1997. The mass to charge ratio organizes the minimum invariant latitude to which the ions penetrate.

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.

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^+) 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 (Mason *et al.* 1995). 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

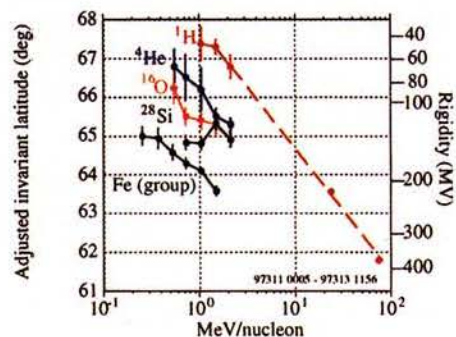


Figure 4. Cutoff latitudes versus mass and energy for selected species from ~ 0.25 - 2 MeV/n. We assume the protons and helium are fully stripped in order to calculate the rigidity scale.

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

^aEnergy dependence seen only in Fe above ~20 MeV/n.^bAverage of 12 events from Sept. 1978 - Sept. 1979.^cNormalization used in the geomagnetic cutoff technique.^dSi energy ranges: 0.4 - 1.25 MeV/n & 1.25 - 2.5 MeV/n.

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.

Because of their higher count rates, we used 19-28 MeV protons in order to correct for the changing cutoffs rather than the heavy ions. The mean invariant latitude of the 19-28 MeV proton cutoff was 63.96°. We scaled the profiles of low energy ion flux vs. invariant latitude for each pass through the cutoff region (4 passes per orbit) to this mean proton cutoff. We also excluded polar passes with significant structure (variations of >30%) in the 19-28 MeV protons due to varying particle access; particle access was most likely to be non-uniform over the polar caps during the most geomagnetically disturbed intervals of 7 November 1997. We averaged over the remaining 79% of approximately uniform passes from 0005UT on 7 November 1997 to 1156UT on 9 November 1997 for the charge state analysis discussed below.

Figure 3 shows the latitude profiles of 0.85-1.25 MeV/nucleon H, He, O, & Fe, adjusted for the time-variations of Figure 1 and normalized to the average flux of H between 75° to 85°. Note that at the same velocity, different species penetrate to different latitudes depending on their ionization states: assuming He is fully stripped, Figure 3 shows that the mass to charge ratio of ¹⁶O is greater than 2 (i.e. ¹⁶O is not fully stripped), and that Fe has the highest rigidity. We next quantified the cutoff latitudes for each species and energy bin by measuring the latitude at which the flux falls to 50% of its average between 75° to 85°. The resulting charge states were not sensitive to the choice of cutoff threshold.

Figure 4 plots the cutoff latitudes versus energy per nucleon for selected species; note that because of magnetic rigidity, we observe decreasing cutoff latitudes with increasing mass and energy. We used the LICA H & He measurements, assuming full ionization for these species, as well as the 19-28 MeV protons from PET (again assuming charge +1) to establish the cutoff invariant latitude as a function of rigidity between 61.5° and 67.5° (see the right-hand scale of Figure 5). Note that the range of observed cutoffs of all heavy ions measured by LICA fall within the calibration derived from H & He; there is no need for a highly uncertain extrapolation of the calibration beyond the H & He cutoffs.

Above 10 MeV/nucleon, the cutoff technique is essentially the same as that used at lower energies; here we accounted for the time-dependence of the cutoffs with 7-12 MeV H measured in each polar pass with the MAST sensor (after Leske et al. 1995). We used 19-28 MeV protons, 7-12 MeV H, as well as the cutoff-rigidity relations observed in the October/November 1992 events to derive the cutoff-rigidity relation and the resulting charge state uncertainties above 10 MeV/nucleon.

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 5 compares the charge states of Si & Fe during 6-9 November 1997 with those measured with the same

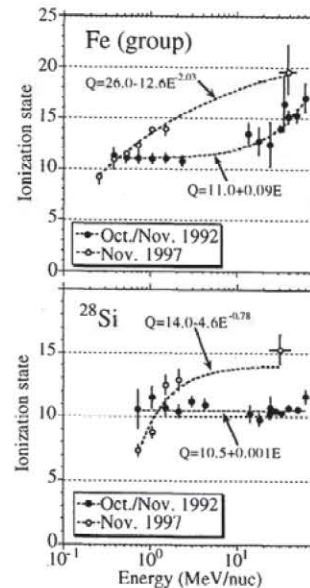


Figure 5. Ionization states of Fe(group) and ²⁸Si versus energy of the 6 November 1997 event (open circles), in contrast to the October/November 1992 events (filled circles) also measured with the geomagnetic cutoff technique on SAMPEX. The dashed curves are fits to the data using the functions listed in the figure.

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.

Discussion & Conclusions

To date we have examined the ionization states of particles in 2 large SEP events with the geomagnetic cutoff technique: October/November 1992 and 6 November 1997. In each case, the time-intensity profiles suggest a superposition of at least 2 distinct particle injections observed above 10 MeV/nucleon, as well as local particle acceleration in at least 1 interplanetary shock passage. However, the ionization states of Si and Fe in these 2 event time periods, contrasted in Figure 5, have strikingly different dependences on energy. The origin of the difference 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.

In an accompanying paper, Mobius *et al.* [1998] report on ~0.2 - 1 MeV/nucleon ionization states measured in the 6 November 1997 event using an electrostatic deflection technique on board the ACE spacecraft. They also found increasing ionization states for O-Fe with increasing energy below 1 MeV/nucleon, but with a *mean* Fe charge state about 2 charge units higher than measured on SAMPEX. Only by shifting the cutoff latitudes observed with SAMPEX upward by ~0.6° could the Fe cutoffs presented here correspond to charge states that are 2 units higher; the observed latitude profiles rule out such a large systematic offset.

The electrostatic deflection technique does not extend beyond ~1 MeV/nucleon, so there is no opportunity to compare the two techniques at the higher energies. Based upon a comparison of SEP isotopic abundances measured on ACE in these November 1997 events and solar system isotopic abundances, Cohen *et al.* [1998] deduce high charge states for Fe (~+19) and Si (~+12) between 10 to 60 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.

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J. E. Mazur and M. D. Looper, The Aerospace Corporation, 270 Coral Circle, El Segundo CA 90245. (email: joseph.mazur@aero.org; mark.looper@aero.org)

G. M. Mason, Department of Physics, University of Maryland, College Park, MD 20742. (email: mason@sampx3.umd.edu)

R. A. Leske and R. A. Mewaldt, California Institute of Technology, Pasadena, CA 91125. (email: ral@srl.caltech.edu; mewaldt@srl.caltech.edu)

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