SH 3.5.03

Ionic Charge State Measurements of Solar Energetic Particles Using SAMPEX/MAST

D.J. Larson[1], R.A. Leske[1], R.A. Mewaldt[1], E.C. Stone[1], A.C. Cummings[1], and T.T. von Rosenvinge[2]
[1]*California Institute of Technology, Pasadena, CA 91125, USA*
[2]*Goddard Space Flight Center, Greenbelt, MD 20771, USA*

Abstract

The solar energetic particle events (SEP) of 1998 are surveyed using the *MAST* instrument on the *SAMPEX* satellite. *MAST* has been operational since 1992 and can effectively measure heavy ($Z > 5$) solar energetic particles with kinetic energies ranging from 15 to 250 MeV/nucleon. Mean charge states of abundant elements from C to Fe are determined using the geomagnetic field as a particle rigidity filter. The SEP charge states provide further clues toward understanding the abundance variations in SEP events.

1 Introduction:

Observations of solar energetic particle (SEP) events over the solar cycle enhance our understanding of the processes taking place between the Sun and Earth. The pathlength that a high energy particle may traverse between the Sun and Earth depends on the location of the initial acceleration, density of the ambient material, and on scattering processes between here and the sun. In some cases this pathlength may be sufficient to increase the mean charge through stripping. Measurements of charge states may thus serve both as a probe of the temperature in the source region and as a sensitive probe of the pathlengths and their energy dependence encountered during SEP acceleration and subsequent transport to Earth.

The Solar, Anomalous, and Magnetospheric Particle Explorer (*SAMPEX*) satellite was launched into a 675 x 512 km 82° inclination Earth orbit on July 3, 1992 (Baker *et al.*, 1993). The Mass Spectrometer Telescope (*MAST*) onboard *SAMPEX* is a silicon solid state detector particle telescope (Cook *et al.*, 1993) which can measure the nuclear charge, Z, mass, M, and total kinetic energy, E, of energetic particles using the conventional dE/dx versus residual energy technique. *MAST* can provide measurements of heavy ($Z > 5$) solar energetic particles with kinetic energies ranging from 15 to 250 $\mathrm{MeV/n}$.

The *SAMPEX* orbit transits portions of both polar caps about fourteen times per day. This allows *MAST* to monitor the portion of the geomagnetic field where the solar energetic particles have free access. For identical elemental ions of the same energy, a partially stripped ion will have a higher rigidity and access to lower magnetic latitudes than a fully stripped ion. A benefit of the satellite's orbit through the geomagnetic field is that particle deflection effects can assist in the analysis of the observations (Leske *et al.*, 1995, Mazur *et al.*, 1999) using a geomagnetic cutoff technique that will be briefly described.

The geomagnetic cutoff technique of Leske *et al.*(1995, 1996) uses measurements of how the cutoff varies with time, element, and the particle energy, to deduce a cutoff-rigidity relation and determine the mean charge of the particles. The advantage of this technique is that is does not rely upon static dipole based models which relate the cutoff rigidity to the invariant latitude. These models are not particularly accurate at either high latitudes or low rigidities. The geomagnetic cutoff technique uses the actual particle data to deduce the cutoff relation.

The magnetic rigidity, defined as the ratio of momentum to charge, provides a convenient organizing measure for particles of a specific charge, mass, and energy. At each point along the orbit of *SAMPEX*, the Earth's magnetic field will exclude particles below a certain rigidity. Particles with rigidities greater than the local geomagnetic cutoff rigidity will be observed by *MAST*. The latitude where *MAST* stops detecting particles of a specific rigidity is the cutoff latitude, Λ_{C}. The corresponding cutoff rigidity is R_{C}. In order to find Λ_{C}, sufficient events must be observed in a small rigidity interval to establish where Λ_{C} is located. The variation of the magnetic field over time results in Λ_{C} itself being time dependent. Corrections are empirically made for the variability so that the mean Q may then be found.

2 Data Analysis

Calculated tabulations of R_C (Shea *et al.*, 1985) are reasonably accurate at low latitudes or high rigidities, but measurements at higher latitudes and low energies generally find cutoffs lower than predicted (e.g., Fanselow & Stone, 1972). An added obstacle are geomagnetic disturbances which cause Λ to vary from that under quiescent conditions in ways difficult to model at low rigidities. These problems are addressed empirically.

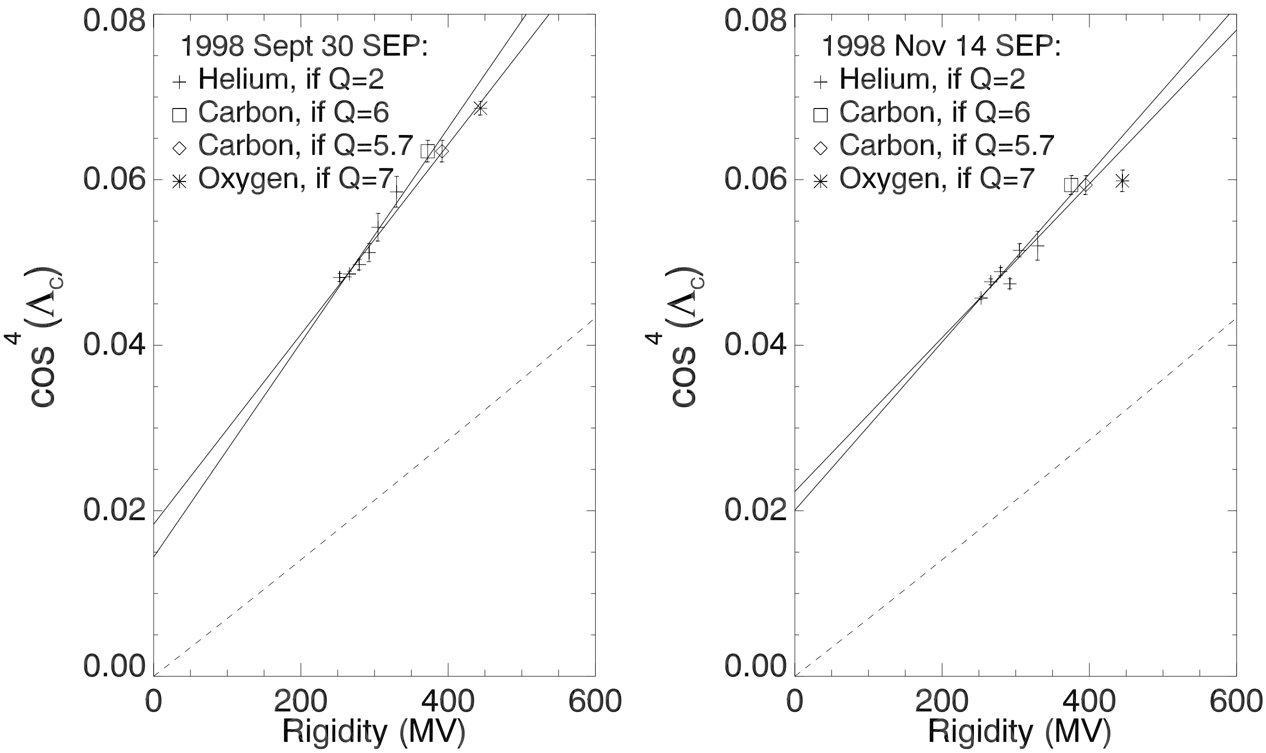

Figure 1: Plot of $\cos^4(\Lambda_C)$ vs. rigidity for He (*vertical bars*), C (*squares, diamonds*), and O (*asterisks*) for the 1998 September 30 SEP (*left*) and 1998 November 14 SEP (*right*) events, assuming the charge states indicated. Limiting cases for the cutoff–rigidity relation adopted here are the fits to the He and C data (*solid lines*), one for each plotted C charge state. The Störmer model prediction using the western cutoffs (Smart & Shea 1993) is indicated by the dashed line.

To accurately determine Λ_C for heavy ions, the detected particles must be summed over the duration of the solar energetic particle (SEP) event to obtain sufficient statistics. First, the time variations of the cutoff must be corrected.

Using the *MAST* rate which responds to He nuclei at $\sim 8 - 15$ MeV/n (Z2 rate), Λ_C is measured for each of the four cutoff crossings per orbit (entry and exit of the two poles) during the SEP event, to within $\sim 0.2°$, (see Leske *et al.*, 1995). The cutoffs show little correlation with the value of the Z2 rate, but are well–correlated with the geomagnetic activity index *Dst*. The correlation with *Dst* is good but not completely suitable due to scaling and offset differences from event to event so the actual measurements are used rather than any proxy. The observed time dependence is then corrected by subtracting the difference between the Z2 cutoff for the nearest crossing and the mean value of the Z2 cutoff from the value of Λ for each pulse height analyzed event.

For each of the abundant elements, Λ_C is determined in small energy intervals, typically 10 MeV/n for heavy ions, and 1 MeV/n for He, although for energies higher than 13 MeV/n, a wider bin is used for helium due to reduced statistics. For each interval, a distribution of relative flux vs time–dependence–corrected Λ is produced whose shape resembles an edge and plateau. The cutoff is determined from a linear fit to the cutoff edge, with an overall uncertainty which includes the uncertainty in the location of the plateau level. $\Lambda_{\rm C}$ is then defined to be the value of Λ from the fit edge where the rate is one half of its mean value as defined by the plateau (see Leske, 1996).

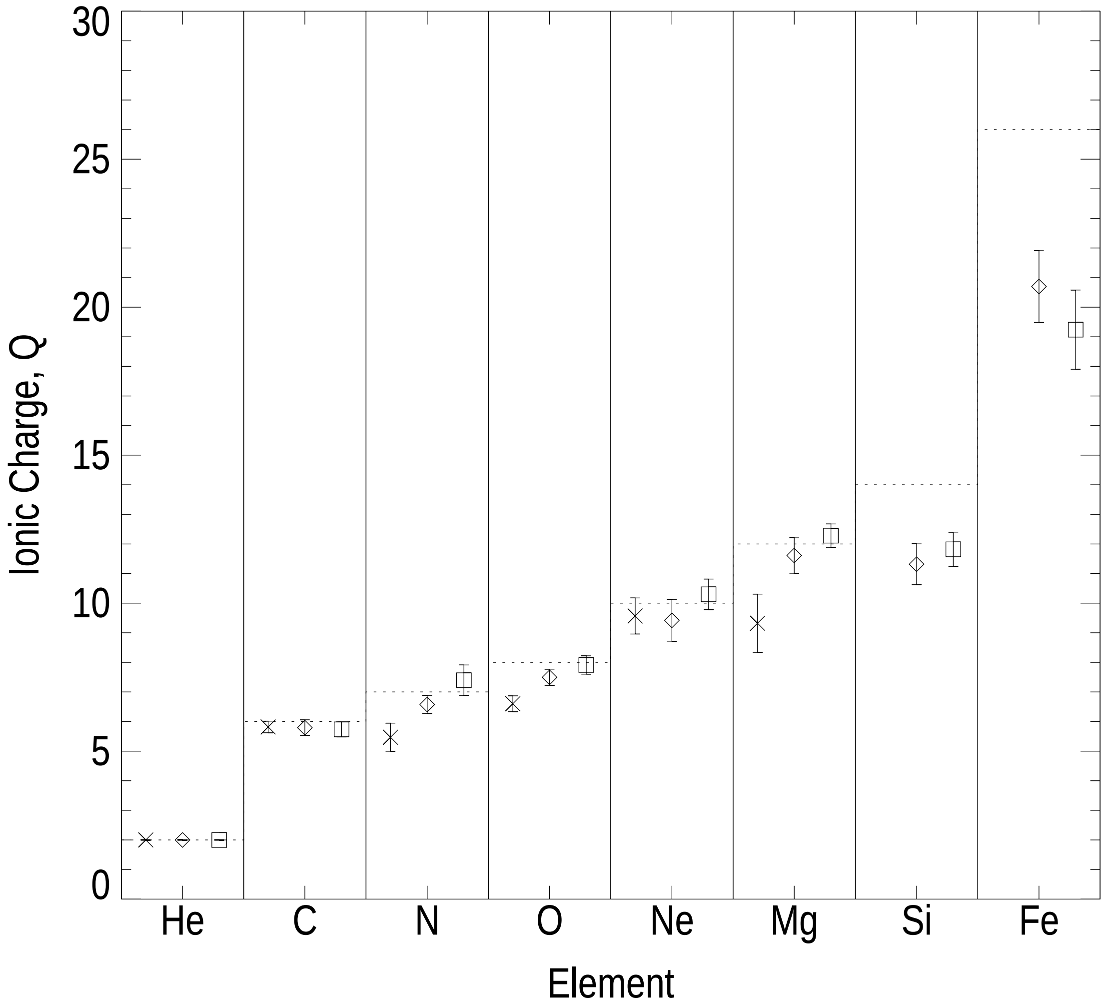

Figure 2: Measured values of the mean Q for the indicated elements from the 1998 August 24 SEP event (*crosses*), 1998 September 30 SEP event (*diamonds*), and the 1998 November 14 SEP event (*squares*). The August SEP event was a gradual event with fluxes of Si and Fe too low to obtain accurate cutoff estimates and charge state estimates. The dashed line marks the fully stripped ($Q = Z$) value of Q for each element. The calculated charge states were normalized to $Q = 2$ for He and $Q = 5.7 - 6$ for C.

To derive the cutoff–rigidity relation for a particular event, three primary assumptions are made; first that *SEP* He is fully stripped, second, guided by the Störmer model (Störmer, 1930, 1955), it is assumed that $R_{\rm C}$ is linearly related to $\cos^4(\Lambda_{\rm C})$, and third that the mean ionic charge of C is somewhere between $+6$ (fully stripped) and $+5.7$ as measured at low energies (Luhn *et al.*, 1985). Linear fits in Figure 1 through the He and C data for each of the SEP events provide the limiting–case empirical relations between $\Lambda_{\rm C}$ and $R_{\rm C}$ required to obtain the mean charge states for other elements.

The mean values for Q shown in Figure 2 are found using the fits in Figure 1, with the uncertainties shown being dominated by the uncertainty in the C ionic charge state. The limited statistics in the events complicate the determination of the cutoff latitudes for high Z elements, and undoubtedly contribute systematic uncertainties which have not yet been accounted for in the current analysis.

Other studies (see review by Kahler 1992) indicate that SEP acceleration in gradual–type events occurs primarily at the shock driven by a fast coronal mass ejection (CME), rather than at the flare site itself. Our results for the gradual 1998 August 24 SEP trend towards lower charge states than the 1998 November 14 event which may be impulsive (Cohen *et al.*, 1999). This is consistent with the earlier observations (Luhn *et al.*, 1985, Luhn *et al.*, 1987) of higher charge states for Fe and Si in impulsive events than in gradual events.

3 Results and Discussion

This report has presented preliminary mean charge states for the gradual event of 1998 August 24 as well as the Fe rich 1998 September 30 and 1998 November 14 SEP events. Including high energy proton data for these events from the *PET* telescope on *SAMPEX* will augment the calibration curves presented in Figure 1.

The charge state determinations made using the SIS instrument on *ACE* by Cohen *et al.* for the 1998 November 14 event corroborate our measurements with a different analysis approach. The *SAMPEX* mean charge states are consistently higher for Ne and Mg but agree for Si and Fe. The differences at lower Z are probably attributable to the different techniques employed to determine the charge state values and systematic uncertainties in both approaches. The technique used by Cohen *et al.* infers the charge state by assuming elemental and isotopic fractionation are characterized by the same Q/M dependence. The *ACE* Si measurements were within half a charge unit of the *SAMPEX* values and a quarter of a charge unit for the Fe measurements (Cohen *et al.*, 1999) and are well within the quoted uncertainties. A similar agreement between the two experiments was also seen for the 6 November 1997 event (Mazur *et al.*, 1999).

There are now a total of about four large solar events that indicate an Fe charge state of 20 at high energies, substantially greater than is observed at lower energies in these large events (e.g. Oetliker *et al.*, 1997, Mazur *et al.*, 1999, Möbius *et al.*1999). The cause of this energy dependence is not yet understood. A possible explanation has been suggested by Barghouty and Mewaldt (1999) who considered the time scales for charge change, ionization-recombination, and shock acceleration in a nonequilibrium model.

This work was supported by NASA under grant NAG5-2963.

References

Baker D. N.,*et al.*, 1993, *IEEE Trans. Geosci. Remote Sensing*, GE-31, 3, 531

Barghouty, A. F. & Mewaldt, R. A., 1999, ApJ, *to be published*

Cohen, C. M. S., *et al.*, 1999 Proc. 26th ICRC (Salt Lake City) paper SH 1.5.07

Cook, W. R., *et al.*, 1993, *IEEE Trans. Geosci. Remote Sensing*, GE-31, 557

Fanselow, J. L., & Stone, E. C. 1972, J. Geophys. Res., 77, 3999

Kahler, S. W. 1992, ARA&A, 30, 113

Leske, R. A., *et al.*, 1995, ApJL 452, L149

Leske, R. A., *et al.*, 1996, *AIP Conference Proceedings 374*, High Energy Solar Physics, 86

Luhn, A., et al., 1985, Proc. 19th ICRC (La Jolla), 4, 241

Luhn, A., Klecker, B., Hovestadt, D., & Möbius, E., 1987, ApJ 317, 951

Mazur, J. E., *et al.*, 1999, GRL 26,(2)173

Möbius, E. M., *et al.*, 1999, GRL, 26, 145

Oetliker, M., *et al.*, 1997, ApJ, 477, 495

Shea, M. A., Smart, D. F., Gentile, L. C., 1985 Proc. 19th ICRC (La Jolla), 5, 332

Smart, D. F., & Shea, M. A. 1993 Proc. 23rd ICRC (Calgary), 3, 781

Störmer C., 1930, *Z. Astrophys.*, 1, 237

Störmer C., *The Polar Aurora*, Clarendon Press, Oxford, 1955