1995ICRC....4..461L

Measurements of the Ionic Charge States of Solar Energetic Particles at 15-70 MeV/nucleon

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Abstract

The mean charge states of abundant heavy ions with $\sim 15-70$ MeV/n in the two large solar energetic particle (SEP) events of 1992 October 30 and November 2 have been determined using measurements of invariant latitude of the geomagnetic cutoffs as a function of time, particle energy, and element from the Mass Spectrometer Telescope (MAST) on *SAMPEX*. The deduced charge state values are in good agreement with the mean values measured directly in previous SEP events at much lower energies of ~ 1 MeV/n, with inferred equilibrium source temperatures of typically 2×10^6 K, which provides additional evidence that SEPs in gradual-type events are accelerated coronal material.

1 Introduction and Data Analysis

The Mass Spectrometer Telescope (MAST) is a silicon solid state detector particle telescope [1], and as such is not directly sensitive to a particle's ionic charge, Q. However, from measurements of the nuclear charge, Z, mass, M, and total kinetic energy, E, provided by MAST, the mean Q may be found if the mean rigidity can also be determined. Since at any point in the 82° inclination orbit of *SAMPEX* only those particles with rigidities greater than the local geomagnetic cutoff rigidity, R_C, are detected, the mean rigidity of a collection of events can be found if the invariant latitude of the cutoff, Λ_C, can be determined, and if the relation between Λ_C and R_C is known. While calculated tabulations of R_C [2] are reasonably accurate at low latitudes or high rigidities, measurements at higher latitudes and low energies generally find cutoffs lower than predicted (e.g., [3]), and geomagnetic disturbances often cause Λ to vary from that under quiescent conditions in ways difficult to model at low rigidities [4]. However, we can address the problem empirically.

To accurately determine Λ_C for heavy ions, the detected particles must be summed over the entire duration of the solar energetic particle (SEP) event to obtain sufficient statistics, but first any time variation of the cutoff must be corrected. Using the MAST Z2 rate (which responds to He nuclei at $\sim 8-15$ MeV/n), we can actually *measure* Λ_C for each of the four cutoff crossings per orbit during the SEP events, to within $\sim 0.2°$. Figure 1 shows a typical profile of this rate as a function of invariant latitude, Λ, for a single polar crossing. We define Λ_C to be the value of Λ at which the rate is one half of its mean value above 70°.

The resulting measured Z2 cutoff location is shown as a function of time in the lower panel of Figure 2, where curves for all four crossings per orbit are superposed. The curve for exiting the north polar region has been lowered by 1° in this figure to better illustrate the close agreement in the shape of all four curves; these crossings occurred nearest to noon in magnetic local time and therefore exhibited cutoffs at consistently higher Λ due to the day–night effect [3]. As shown in Figure 2, the

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cutoffs show little correlation with the value of the Z2 rate, but are well–correlated with the geomagnetic activity index *Dst* (Solar–Geophysical Data prompt reports). Since the correlation is not perfect, we use our measurements rather than any model predictions to correct for the observed time dependence, 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 5 MeV/n for heavy ions, and 1 MeV/n for He. For each interval, a distribution of relative flux vs time–dependence–corrected Λ is produced whose shape resembles that in Figure 1, with a clear 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. To derive a cutoff–rigidity relation, we assume 1) that SEP He is fully stripped at $8 - 15$ MeV/n, as suggested by recent measurements [5], 2) that the ionic charge of C is somewhere between +6 (fully stripped) and +5.7, as measured at low energies [6], and 3) that R_C is linearly related to $\cos^4(\Lambda_C)$, as in the Störmer model [7], and as is supported by our data (Figure 3). Based on these assumptions, linear fits through the He and C data (Figure 3) for each of the SEP events provide the limiting–case empirical relations between Λ_C and R_C required to obtain the mean charge states for other elements. Additional details of the analysis and results may be found in [8].

2 Results and Discussion

The O measurements in Figure 3 assume for illustration purposes that O is fully stripped. Because they lie significantly to the left of even the fully stripped C points with similar values of Λ_C, the O rigidity must be higher than shown. Therefore, O can not be fully stripped at these energies, regardless of the charge state of C and independent of any theoretical or empirical cutoff–rigidity relation. Similar arguments show that all heavier ions are only partially stripped.

The mean values for Q listed in Table 1 are found using relations as shown in Figure 3, with uncertainties typically dominated by the uncertainty in the C ionic charge state. These values are consistent with those measured at other energies, and are similar to those expected from equilibrium calculations of collisional ionization for a plasma at 2×10^6 K [9, 10], as shown in Figure 4. The inferred source temperatures for Mg and Ne (Table 1) are higher than for the other elements, confirming the Luhn et al. [6] findings, and suggesting that equilibrium temperature calculations, particularly for 2–electron atoms, may need refining, that additional ionization mechanisms may be important, or that the assumption of equilibrium is not valid. Our Na and Al temperatures have large uncertainties, as their charge states fall in a region where little change is expected in Q with temperature [9], while Ar, Ca, and Ni are all consistent with $\sim 2 \times 10^6$ K, suggesting that the source material for large SEP events is likely to be ambient coronal material, rather than the hotter flare plasma.

Similar measurements during these same SEP events from other instruments on *SAMPEX* by Mason et al. [11] at the lower energies of $0.5 - 5$ MeV/n agree with the MAST charge state values, except for Fe, for which they report $Q = 11.04 \pm 0.22$. Although the Fe cutoffs for MAST are at values of $\cos^4(\Lambda_C)$ about a factor of 2 beyond the He and C data (Figure 3) used to define the cutoff–rigidity relation, extrapolations of our relations agree with higher rigidity measurements [12], and we believe our data do not support a Q of 11 at our energies. Our Fe measurements are consistent with no variation in Q with E, but with uncertainties large enough to allow a Q of 11 if

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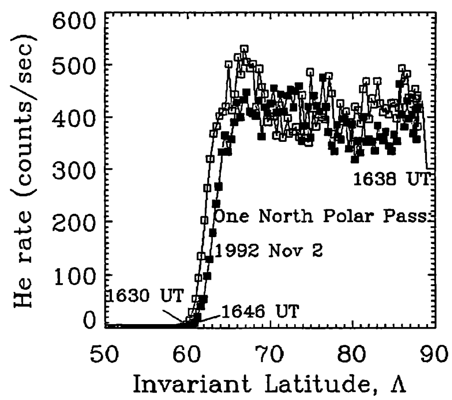

Fig. 1 – Rate of ~8-15 MeV/n He (Z2) vs Λ for a single passage into (open squares) and out of (filled squares) the north polar cap.

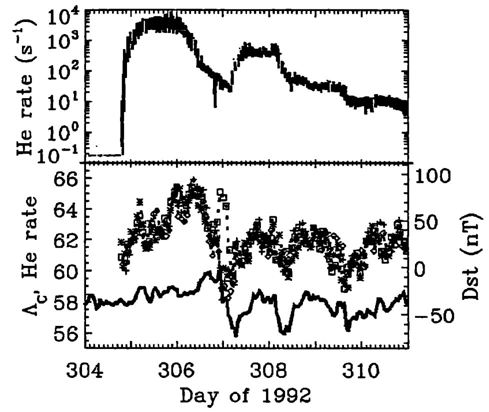

Fig. 2 – Top: The MAST Z2 rate during the two SEP events. Bottom: Measured Λ_C (left axis) for the Z2 rate vs time, for crossings entering (asterisks) and exiting the north polar cap, lowered by 1° (squares), and entering (pluses) and exiting (diamonds) the south polar cap, compared with Dst (right axis; heavy line).

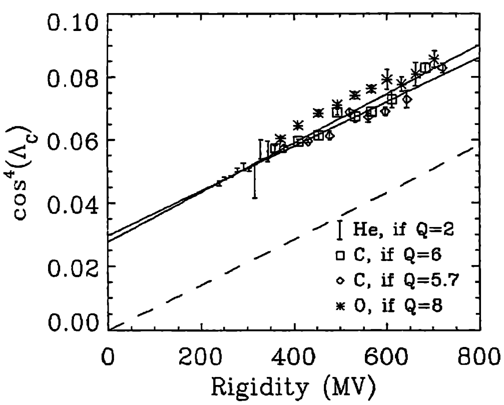

Fig. 3 – Plot of $\cos^4(\Lambda_C)$ vs rigidity for He, C, and O for the 1992 November 2 SEP event, assuming the charge states indicated. Fits to the He and C data (solid lines), one for each plotted C charge state, show the limiting cases for our cutoff–rigidity relation, compared with the Störmer western cutoff [7] (dashed).

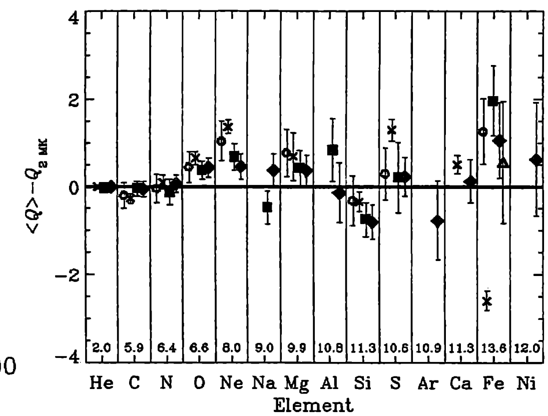

Fig. 4 – Difference between mean measured values of Q and those expected for a 2×10^6 K source plasma [9, 10], with the value of Q_{2MK} for each element indicated along the bottom. Data are from the 1992 October 30 SEP event (squares) and 1992 November 2 event (diamonds) at ~15-70 MeV/n, Luhn et al. [6] at ~0.3-3 MeV/n (circles), Mason et al. [11] at ~0.5-5 MeV/n (crosses), and Tylka et al. [13] at ~200-600 MeV/n (triangle).

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linearly extrapolated to low energies. However, taken together with our results, the measurement at 200-600 MeV/n [13] does not suggest an increasing Q with E, at least beyond $\sim$ 20 MeV/n.

The close agreement between our results and those of Luhn et al. [6] validates the use of the low energy Q/M values to organize SEP elemental abundances at energies up to 50 MeV/n (e.g., [14]), and shows that little or no additional stripping occurs for most elements during acceleration to these higher energies. Preliminary calculations using a computer code designed to find the charge states of heavy ion accelerator beams [15] suggest that at 50 MeV/n, even neutral Fe would reach a Q of +17 after passing through less than 600 μg cm^{-2} of H. This is considerably lower than the present upper limit of 30 mg cm^{-2} on the amount of material SEPs encounter [16], and again points to acceleration in a low density region.

This work was supported by NASA under contract NAS5–30704 and grant NAGW–1919.

TABLE 1

		SEP Event #1 (1992 Oct 30)		SEP Event #2 (1992 Nov 2)	
	Z	$<Q>$	T (MK)[a]	$<Q>$	T (MK)[a]
He	2	1.97 ± 0.07		2.00 ± 0.01	
C	6	5.86 ± 0.17	> 0.77	5.85 ± 0.17	> 0.76
N	7	6.30 ± 0.30	1.95 ± 0.30	6.49 ± 0.20	2.14 ± 0.26
O	8	6.93 ± 0.20	2.37 ± 0.22	6.99 ± 0.22	2.45 ± 0.25
Ne	10	8.68 ± 0.30	3.91 ± 0.64	8.47 ± 0.28	3.39 ± 0.66
Na	11	8.50 ± 0.39	1.09 ± 0.20	9.36 ± 0.37	3.67 ± 1.65
Mg	12	10.35 ± 0.40	4.63 ± 2.32	10.29 ± 0.35	4.38 ± 2.18
Al	13	11.63 ± 0.73	7.53 ± 4.96	10.66 ± 0.68	4.17 ± 2.69
Si	14	10.57 ± 0.39	1.76 ± 0.11	10.51 ± 0.40	1.75 ± 0.12
S	16	10.82 ± 0.81	2.02 ± 0.26	10.84 ± 0.44	2.04 ± 0.14
Ar	18			10.08 ± 0.91	1.67 ± 0.39
Ca	20			11.46 ± 0.49	2.05 ± 0.27
Fe	26	15.59 ± 0.81	3.90 ± 1.49	14.69 ± 0.86	2.59 ± 0.53
Ni	28			12.62 ± 1.30	2.04 ± 0.22

[a] Based on equilibrium calculations of [9, 10]

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