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MEASUREMENTS OF THE IONIC CHARGE STATES OF SOLAR ENERGETIC PARTICLES USING THE GEOMAGNETIC FIELD

R. A. Leske, J. R. Cummings, R. A. Mewaldt, and E. C. Stone
California Institute of Technology, Pasadena, CA 91125

and

T. T. von Rosenvinge
NASA/Goddard Space Flight Center, Greenbelt, MD 20771
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ABSTRACT

The mean charge states of C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Fe, and Ni ions with ∼15–70 MeV nucleon^{-1} in the two large solar energetic particle (SEP) events of 1992 October 30 and November 2 have been determined using measurements of the invariant latitude of the cosmic-ray cutoffs of these elements from the Mass Spectrometer Telescope on the polar-orbiting *SAMPEX* satellite. 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 nucleon^{-1}. The inferred equilibrium source temperatures are confirmed to be typically 2×10^6 K, which provides additional evidence that SEPs in gradual-type events are accelerated coronal material.

Subject headings: Sun: corona — Sun: flares

1. INTRODUCTION

Recent work indicates that solar energetic particle (SEP) acceleration in gradual-type SEP events occurs primarily at the shock driven by a fast coronal mass ejection (CME), rather than at the flare site itself (see review by Kahler 1992). Direct measurements of the ionic charge states of SEPs at ∼1 MeV nucleon^{-1} in gradual-type events (Luhn et al. 1985) support this view, as the charge states are consistent with temperatures of 1–2×10^6 K (Mullan & Waldron 1986), which are more typical of coronal material than of ∼10^7 K (Doschek 1991) flare plasma. At higher energies, if particles traverse a longer pathlength during the acceleration process and if the density of the ambient material is sufficiently high, their mean charge state may be increased by electron stripping. Measurements of charge states may thus serve as a sensitive probe of the pathlengths and their energy dependence encountered during SEP acceleration and subsequent transport to Earth.

Previous studies at low energies (Luhn et al. 1985) employed electrostatic deflection to measure ionic charge states directly. Above energies of a few MeV nucleon^{-1} this becomes impractical. The effects of deflection in Earth's magnetic field, however, are detectable at much higher energies, since partially stripped ions have a higher rigidity and access to lower magnetic latitudes than fully stripped ions of the same element and energy. Recent measurements using this effect have found the mean ionic charge states of SEP O at ∼10 MeV nucleon^{-1} (Boberg et al. 1993) and Fe at ∼200–600 MeV nucleon^{-1} (Tylka et al. 1995) to be consistent with the Luhn et al. (1985) low energy values. These results require model calculations of the rigidity-dependent integrated exposure time, since the passive nuclear track detectors used could not directly measure spatial and temporal distributions of the ions during exposures ranging from weeks to years. In this Letter, we take advantage of the temporal resolution provided by the Mass Spectrometer Telescope (MAST) to measure the spatial distributions of SEPs along the orbit of the *Solar, Anomalous, and Magnetospheric Particle Explorer* (*SAMPEX*) satellite. From observations of the invariant latitude of the geomagnetic cutoff as a function of time, particle energy, and element during the large SEP events of 1992 October 30 and November 2, the relative charge states for 13 elements (several not previously measured) are determined at energies of ∼15–70 MeV nucleon^{-1}, about a factor of 30 higher than is possible with direct measurements. We compare our results to theoretical calculations and other measurements and discuss the implications for SEP acceleration and transport.

2. DATA ANALYSIS

MAST is a silicon solid state detector particle telescope (Cook et al. 1993), and measures the nuclear charge, Z, mass, M, and total kinetic energy, E, of energetic particles using the conventional dE/dx versus residual energy technique. Although MAST achieves good elemental and isotopic resolution for SEPs (Selesnick et al. 1993), it is not directly sensitive to the ionic charge, Q, as incident ions are quickly stripped in traversing the material of the instrument. However, from measurements of Z, M, and E, 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. (For a centered dipole, the invariant latitude for a given field line would be the latitude relative to the magnetic equator at which that field line intersects Earth's surface. See Roederer 1970 for more details.) While calculated tabulations of R_C are reasonably accurate at low latitudes or high rigidities (Shea & Smart 1983), measurements at higher latitudes and low energies generally find cutoffs below simple model expectations (e.g., Fanselow & Stone 1972; Seo et al. 1991). In addition, geomagnetic disturbances that accompany solar flares often cause the cutoff location to vary from that under quiescent conditions, and only recently has it been shown to be possible

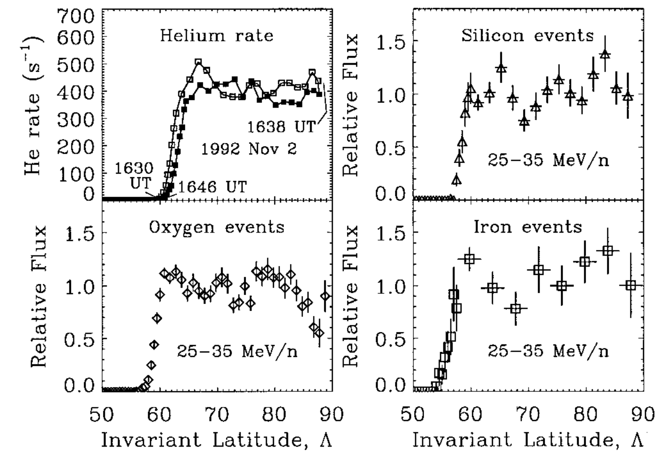

FIG. 1.—*Top left*: Rate of ~8–15 MeV nucleon^{-1} He (Z2) vs. Λ (calculated using the IGRF 1990 field model), used in measuring the time variation of the cutoff, for a single passage into (*open squares*) and out of (*filled squares*) the north polar cap. Distributions of O (*bottom left*), Si (*top right*), and Fe events (*bottom right*) summed over the second SEP event at 25–35 MeV nucleon^{-1} vs. time-corrected Λ, used in determining *Q*. The statistical uncertainties shown are larger at the high-latitude plateau because of increased proton-induced dead-time losses.

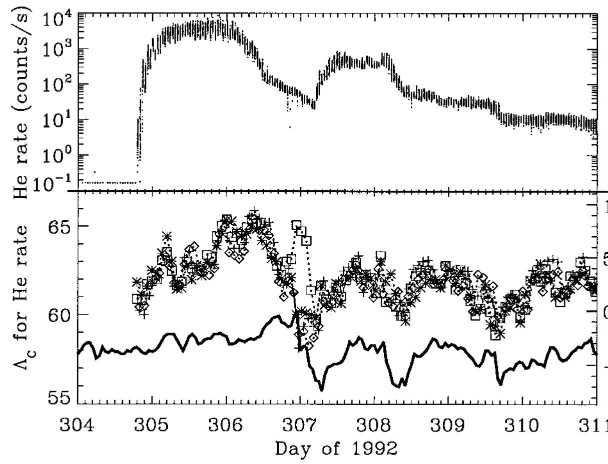

FIG. 2.—*Top*: The MAST Z2 rate vs. time during the two SEP events, for $\Lambda > 66°$. *Bottom*: Measured Λ_C for the Z2 rate vs. time, for crossings entering (*asterisks*) and exiting (*squares*) the north polar cap, lowered by 1° (see text), and entering (*plusses*) and exiting (*diamonds*) the south polar cap, compared with Dst (*heavy line*).

to model the variation at low rigidities (Boberg et al. 1995). For this work, we address the problem empirically.

The SEP events discussed here are the largest observed by MAST to date, reaching peak fluxes more than four orders of magnitude greater than solar quiet time levels, and are therefore essentially uncontaminated by anomalous or galactic cosmic rays. Even with fluxes this high, however, to determine Λ_C for heavy ions with sufficient statistics, the detected particles must be summed over the entire duration of the SEP event. Before doing so, any time variation of the cutoff must be corrected. Using the MAST Z2 rate (which responds to He nuclei at ~8–15 MeV nucleon^{-1}) we can measure Λ_C for He for each of the four cutoff crossings per orbit during the SEP events to within ~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 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 (MLT) and therefore exhibited cutoffs at consistently higher Λ due to the day-night effect (e.g., Fanselow & Stone 1972). Note that a higher cutoff for the north polar exit is clearly evident even in the example shown in Figure 1. Additional variations correlated with MLT have not been corrected in this figure, as it is not necessary to do so. The Z2 rate, also shown in Figure 2, indicates that both these SEP events were of the gradual type, and quite large, with significantly elevated count rates observed for more than a week. The cutoffs show little correlation with the value of the Z2 rate but are well correlated with the geomagnetic activity index *Dst* (Solar-Geophysical Data), with the exception that *Dst* appears to lag behind the cutoff on day 306, possibly because of the passage of a shock (Solar-Geophysical Data). Since model predictions based on *Dst* are not used for our time-dependent correction, this discrepancy has no effect on our results.

To correct for the observed time dependence, the difference between the Z2 cutoff for the nearest crossing and the mean value of the Z2 cutoff for the south polar exits (which occurred closest to midnight in MLT) was subtracted from the value of Λ for each pulse-height analyzed event. Analysis of the count rate of protons from other *SAMPEX* instrumentation shows that the amplitude of the time variations is ~20% larger at half the Z2 rigidity. This effect is not presently included in our analysis; preliminary attempts to do so result in differences of less than ~0.2 charge units from the *Q* values reported here.

For each of the abundant elements, Λ_C is determined in small energy intervals, typically 5 MeV nucleon^{-1} for heavy ions, and 1 MeV nucleon^{-1} for He. The number of events in each time dependence–corrected Λ bin for each energy interval is corrected for instrumental dead time, chance coincidences, and exposure time at that Λ to produce a distribution of relative flux versus Λ as illustrated for several elements in Figure 1, with a clear edge and plateau. The cutoff is again taken to be the latitude where the flux falls to half its mean value at the polar plateau and is determined from a linear fit to the cutoff edge, with an overall uncertainty based on both the uncertainties in this fit and in the flux level at the plateau. As a test of the time-dependent corrections, both SEP events were divided into two time intervals, with the cutoffs for each element and energy bin measured in each interval. The only large differences found suggest that He is contaminated by chance coincidences with protons before ~02:30 UT on day 306 in the first SEP event, and we therefore omit He data from this period. This omission is not necessary for the heavier elements, which are essentially unaffected by such chance coincidences, or for the second event, where the rates were lower and the contamination less severe.

To derive a cutoff-rigidity relation, we make three assumptions. First, we assume that SEP He is fully stripped at 8–15 MeV nucleon^{-1}. Earlier SEP measurements suggest that the He^{+} abundance would be at most a few percent at these energies (Gloeckler et al. 1981), while recent measurements (Gloeckler et al. 1994) indicate that He^{+} observed in the inner solar system may be largely due to interstellar pickup ions and not directly associated with SEP events at all. Second, to

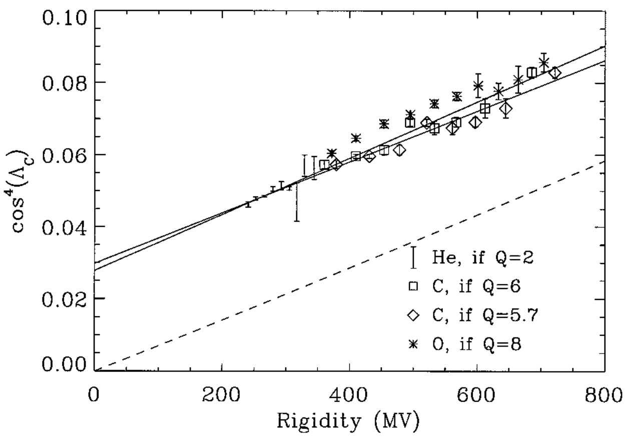

FIG. 3.—Plot of $\cos^4(\Lambda_C)$ vs. rigidity for He (*vertical bars*), C (*squares, diamonds*), and O (*asterisks*) for the 1992 November 2 SEP event, assuming the charge states indicated. Limiting cases for the cutoff-rigidity relation adopted here are the fits to the He and C data (*solid lines*), one for each plotted C charge state, and are compared with the Störmer model western cutoff (Smart & Shea 1993; *dashed curve*).

directly establish the cutoff-rigidity relation at the higher energies of the heavier ions without extrapolating in energy from He, we assume 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). Luhn & Hovestadt (1987) concluded that the SEP charge states observed near 1 MeV nucleon^{-1} underwent negligible alteration because of electron attachment or stripping during transport to Earth. If more material were encountered at higher energies (due, perhaps, to longer confinement times at the shock), the resulting charge states could only be higher, since the electron stripping cross section is about five orders of magnitude larger than the attachment cross section at these energies (Crawford 1979). Finally, guided by the Störmer model (Smart & Shea 1993), we assume that R_C is linearly related to $\cos^4(\Lambda_C)$. Our O data (Fig. 3) are fitted well by a straight line, with a χ^2 of 7.4 for 7 degrees of freedom in the first SEP event and 7.0 for 8 degrees of freedom in the second, but with a large offset from the origin unaccounted for by the Störmer model, independent of the assumed values of Q (for linear fits to any single element). This offset corresponds to free access of particles at $\Lambda \geq 65°$, which is similar to the observed location of the midnight boundary of the electron polar cap (Evans & Stone 1972) and agrees well with other lower rigidity cutoff measurements in these same SEP events (Mason et al. 1995). Based on these assumptions, then, linear fits through the He and C data (Fig. 3) for each of the SEP events provide the desired relations between Λ_C and R_C required to obtain the mean charge states for other elements.

3. 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 cutoff-rigidity relation. Similar arguments show that all heavier species examined here are on average 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 systematic uncertainty in the C ionic charge state. These values are consistent with those measured at low energies and are similar to those expected from equilibrium calculations of collisional ionization for a plasma at 2×10^6 K (Arnaud & Rothenflug 1985; Arnaud & Raymond 1992), as shown in Figure 4. The inferred source temperatures for Ne and perhaps Mg are higher than for the other elements, confirming the Luhn et al. (1985) findings, and suggesting that an additional mechanism such as photoionization due to flare X-rays (Mullan & Waldron 1986) may play an important role, that equilibrium temperature calculations (particularly for two-electron atoms) may need refining, or that the assumption of equilibrium is not valid. Some elements not measured by Luhn et al. (1985), such as Na and Al, have deduced temperatures with large uncertainties since their charge states are found to fall in a region where little change is expected in Q with temperature (Arnaud & Rothenflug 1985), while Ar, Ca, and Ni are 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

TABLE 1

SEP IONIC CHARGE STATES AND CORRESPONDING SOURCE TEMPERATURES

Element	Z	E (MeV nucleon^{-1})	SEP Event 1 (1992 Oct 30) $\langle Q \rangle$	SEP Event 1 (1992 Oct 30) T (MK)[a]	SEP Event 2 (1992 Nov 2) $\langle Q \rangle$	SEP Event 2 (1992 Nov 2) T (MK)[a]	Average of SEP Events 1 & 2 $\langle Q \rangle$	Average of SEP Events 1 & 2 T (MK)[a]
He	2	8–16	2.00[b]		2.00[b]		2.00[b]	
C	6	15–65	5.70–6.00[b]		5.70–6.00[b]		5.70–6.00[b]	
N	7	16–65	6.30 ± 0.30	1.95 ± 0.30	6.49 ± 0.20	2.14 ± 0.26	6.47 ± 0.20	2.11 ± 0.25
O	8	17–70	6.93 ± 0.20	2.37 ± 0.22	6.99 ± 0.22	2.45 ± 0.25	6.95 ± 0.20	2.40 ± 0.22
Ne	10	19–65	8.68 ± 0.30	3.91 ± 0.64	8.47 ± 0.28	3.39 ± 0.66	8.53 ± 0.27	3.56 ± 0.61
Na	11	19–48	8.50 ± 0.39	1.09 ± 0.20	9.36 ± 0.37	3.67 ± 1.65	9.11 ± 0.36	2.84 ± 1.72
Mg	12	20–65	10.35 ± 0.40	4.63 ± 2.32	10.29 ± 0.35	4.38 ± 2.18	10.30 ± 0.34	4.52 ± 2.06
Al	13	21–48	11.63 ± 0.73	7.53 ± 4.96	10.66 ± 0.68	4.17 ± 2.69	11.09 ± 0.58	5.09 ± 3.38
Si	14	22–65	10.57 ± 0.39	1.76 ± 0.11	10.51 ± 0.40	1.75 ± 0.12	10.54 ± 0.37	1.75 ± 0.11
S	16	24–50	10.82 ± 0.81	2.02 ± 0.26	10.84 ± 0.44	2.04 ± 0.14	10.84 ± 0.44	2.04 ± 0.14
Ar	18	25–35			10.08 ± 0.91	1.67 ± 0.39	10.08 ± 0.91	1.67 ± 0.39
Ca	20	26–50			11.46 ± 0.49	2.05 ± 0.27	11.46 ± 0.49	2.05 ± 0.27
Fe	26	28–65	15.59 ± 0.81	3.90 ± 1.49	14.69 ± 0.86	2.59 ± 0.53	15.18 ± 0.73	3.18 ± 0.91
Ni	28	31–45			12.62 ± 1.30	2.04 ± 0.22	12.62 ± 1.30	2.04 ± 0.22

[a] Based on equilibrium calculations of Arnaud & Rothenflug 1985 and Arnaud & Raymond 1992.

[b] Used in normalization.

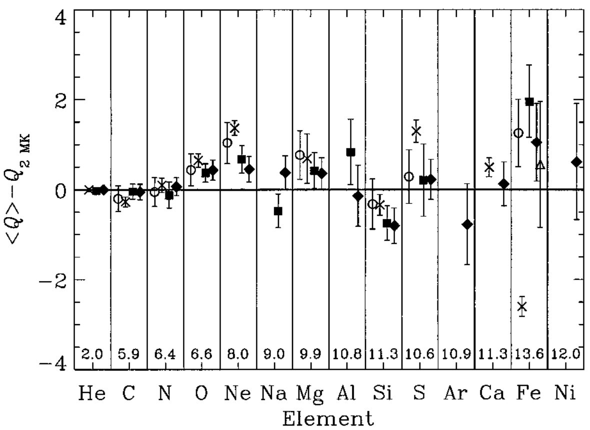

FIG. 4.—Difference between measured values of Q and those expected for a 2×10^6 K source plasma (Arnaud & Rothenflug 1985; Arnaud & Raymond 1992), with the value of $Q_{2\ \mathrm{MK}}$ for each element indicated along the bottom. Data are from the 1992 October 30 SEP event (*squares*) and 1992 November 2 SEP event (*diamonds*) at ~15–70 MeV nucleon^{-1}, Luhn et al. (1985) 12 flare average at ~0.3–3 MeV nucleon^{-1} (*circles*) with 5% systematic uncertainty, Mason et al. (1995) at ~0.5–5 MeV nucleon^{-1} (*crosses*), and Tylka et al. (1995) at ~200–600 MeV nucleon^{-1} (*triangle*).

other instruments on *SAMPEX* by Mason et al. (1995) at the lower energies of 0.5–5 MeV nucleon^{-1} are generally in close agreement with both the MAST and Luhn et al. (1985) charge state values, with the notable exception of Fe, for which Mason et al. report $Q = 11.04 \pm 0.22$. Since the Fe cutoffs for MAST are at values of $\cos^4(\Lambda_C)$ about a factor of 2 beyond those of He and C used to define the cutoff-rigidity relation, the possibility exists that the slight extrapolation of the relation to Fe is inaccurate. This seems unlikely, however, as an extreme extrapolation of our relations by a factor of ~20 predicts a value of R_C at the magnetic equator between the western and vertical Störmer cutoffs (Smart & Shea 1993), which are known to be fairly accurate at low latitudes. Also, recent studies by Selesnick et al. (1995) find that R_C is 5% below the Störmer western cutoff at $\cos^4(\Lambda_C) \sim 0.25$. Using a line through only our He data and this point reduces our Fe charge state in the first event to ~13.7, leaving the value in the second event unchanged. The MAST data do not appear to support a Q as low as 11 at >30 MeV nucleon^{-1}. While our Fe measurements are consistent with no variation in Q with energy, the uncertainties are large enough to allow a Q of 11 at 1 MeV nucleon^{-1} if linearly extrapolated, and correlative studies are underway with other *SAMPEX* investigators to better determine any possible energy dependence.

The close agreement between our results and those of Luhn et al. (1985) validates the use of the low-energy Q/M values to organize SEP elemental abundances at energies up to 50 MeV nucleon^{-1} (e.g., Breneman & Stone 1985) 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 (Pope 1990) suggest that at 50 MeV nucleon^{-1}, even neutral Fe would reach a Q of +17 (2.5 σ above our average measured value) in traversing 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 (Mewaldt & Stone 1983) and again points to acceleration in a low-density region.

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