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Citation: AIP Conference Proceedings **374**, 86 (1996); doi: 10.1063/1.50991
View online: http://dx.doi.org/10.1063/1.50991
View Table of Contents:
http://scitation.aip.org/content/aip/proceeding/aipcp/374?ver=pdfcov
Published by the AIP Publishing

Measurements of the Ionic Charge States of Solar Energetic Particles at 15–70 MeV/nucleon Using the Geomagnetic Field

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The mean charge states of abundant heavy ions with $\sim 15-70$ MeV nucleon^{-1} in the two large solar energetic particle events of 1992 October 30 and November 2 have been determined using measurements of the invariant latitude of the cosmic ray geomagnetic cutoffs as a function of time, particle energy, and element 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 solar energetic particle events at much lower energies of ~ 1 MeV nucleon^{-1}, with inferred equilibrium source temperatures of typically 2×10^6 K. This result provides additional evidence that solar energetic particles in gradual–type events consist of accelerated coronal material.

INTRODUCTION

Recent work indicates that solar energetic particle (SEP) acceleration in gradual–type SEP events occurs primarily at a shock driven by a fast coronal mass ejection (CME), rather than at the flare site itself (1). Direct measurements of SEP ionic charge states at ~ 1 MeV nucleon^{-1} in gradual events (2) find values consistent with temperatures of $1 - 2 \times 10^6$ K (3), much cooler than the $\sim 10^7$ K flare plasma (4) but typical of coronal material, supporting the CME acceleration scenario. At higher energies, if particles traverse a longer pathlength during the acceleration process, their mean charge state may be increased by electron stripping if the density of the ambient material is sufficiently high. In principle, measurements of charge states over broader energy intervals may serve as a sensitive probe of the energy–dependent pathlengths associated with SEP acceleration and subsequent transport to Earth and could help to constrain models of these processes.

Previous studies at low energies (2) employed electrostatic deflection to directly measure ionic charge states, however this becomes impractical above energies of a few MeV nucleon^{-1}. The effects of deflection in the Earth's magnetic field are easily 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. Because of this rigidity filter effect, measurements from the Mass Spectrometer Telescope (MAST) of the spatial distribution of SEPs along the orbit of the Solar, Anomalous, and Magnetospheric Particle Explorer (*SAMPEX*) allowed us to determine SEP charge states, as reported in more detail in (5). Here we summarize the earlier report (5) and provide some additional details on our measurements of relative charge states for abundant elements at energies of $\sim 15 - 70$ MeV nucleon^{-1}, about a factor of 30 higher than is possible with direct measurements, for the large SEP events of 1992 October 30 and November 2. We compare our results to theoretical calculations and other measurements, and discuss the implications for SEP acceleration and transport.

DATA ANALYSIS

MAST is a silicon solid state detector telescope (6) designed to measure the elemental and isotopic composition of energetic particles using the conventional dE/dx vs residual energy technique. Since incident ions are quickly stripped in traversing the material of the instrument, MAST 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. 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. Although rigidity can not be measured for each individual event, the mean rigidity of a collection of events can be found if the invariant latitude (7) of the cutoff, Λ_C, can be determined, and if the relation between Λ_C and R_C is known. Since other measurements at high latitudes and low energies (e.g., (8,9)) generally find cutoffs below simple model expectations (10), and geomagnetic disturbances which accompany solar flares often cause the cutoff location to vary from that under quiescent conditions in ways difficult to accurately model at low rigidities (11), we choose to empirically derive the necessary relation between Λ_C and R_C.

The SEP events discussed here are the largest observed by MAST to date, and were each associated with a major western–limb solar flare, magnetically well connected to the Earth. As reported in the *Daily Summaries of Solar Geophysical Activity*, a class X1.7/2B flare at 22°S, 61°W reached its peak at 1816 UT on 1992 October 30, followed less than 3 days later by a class X9.0 event from the same active region, then several degrees beyond the west limb at 0308 UT on November 2. Both of these gradual–type events were also associated with large CMEs.

The MAST counting rates shown in Figure 1 indicate that during these SEP events significantly elevated count rates were observed for more than a week. Even with fluxes this high, however, the determination of Λ_C for rarer heavy ions with sufficient statistics requires that the detected particles be

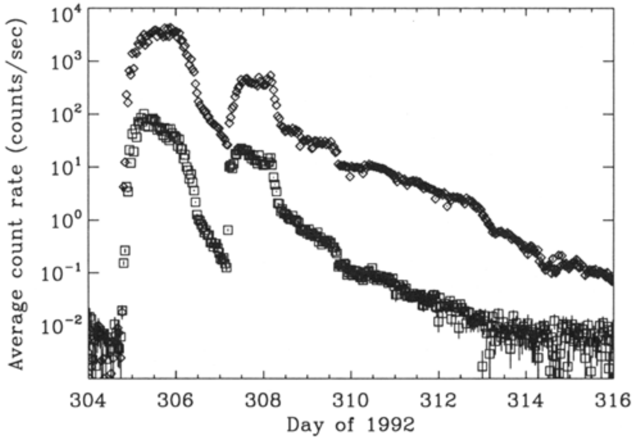


FIG. 1. MAST count rates, averaged over each polar pass ($\Lambda > 66°$) during the two SEP events, for 8-15 MeV nucleon^{-1} He (*diamonds*) and $\sim 12-300$ MeV nucleon^{-1} heavy ions ($Z \geq 3$, *squares*).

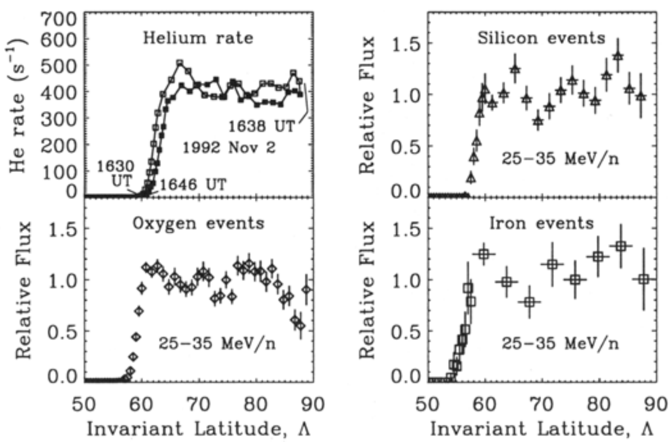


FIG. 2. *Top left:* Rate of $\sim 8-15$ MeV nucleon^{-1} He (Z2) vs Λ (calculated using the IGRF 1990 field model), used in measuring the time variation of the cutoff, for a single passage into (*open squares*) and out of (*filled squares*) the north polar cap. Distributions of O (*bottom left*), Si (*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 due to increased proton–induced dead time losses.

summed over the entire duration of the SEP event. Before this is done, any time variation of the cutoff must first be corrected. Using the MAST Z2 rate (which responds to He nuclei at $\sim 8-15$ 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 $\sim 0.2°$. A typical profile of this rate as a function of invariant latitude, Λ, is shown in Figure 2 for a single polar crossing. The resulting measured time variation in the cutoff location, which is found to be strongly correlated with geomagnetic activity, is used as a template to correct the values of Λ for the heavy ion pulse height events as described in (5).

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 vs Λ as illustrated for several elements in Figure 2, with a clear edge and plateau. The cutoff is taken to be the latitude where the flux falls to half its mean value above 70° 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.

RESULTS AND DISCUSSION

Figure 3 illustrates a small sample of these cutoff measurements, showing Λ_C for C, O, and Si as a function of energy for the second SEP event, which had better heavy ion statistics (after allowing for instrumental dead time) than the first. The cutoff latitude is seen to clearly decrease with increasing energy, qualitatively as expected. Notice that up through at least 50 MeV nucleon^{-1} the O cutoffs are consistently and significantly below the C cutoffs at the same kinetic energy per nucleon. Therefore, the O rigidity must be higher than that of C at the same velocity, and thus O (which was found to be nearly fully ionized with an average measured charge of +7.0 at ~ 1 MeV nucleon^{-1} (2)) 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, as suggested by the Si data in Figure 3.

To obtain more quantitative results, we derive a cutoff–rigidity relation based on three assumptions which are justified and discussed in more detail in (5). First, we assume that SEP He is fully stripped at $8-15$ MeV nucleon^{-1}, as may be inferred from recent measurements (12). Secondly, to directly establish the cutoff–rigidity relation at the higher energies of the heavier ions without a large extrapolation 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 (2). Finally, guided by the Störmer model (13), we assume that R_C is linearly related to $\cos^4(\Lambda_C)$. Our data (Figure 4) support a straight line fit, but with a large offset from the origin unaccounted for by the Störmer model (13). Although it was necessary to assume values for Q in

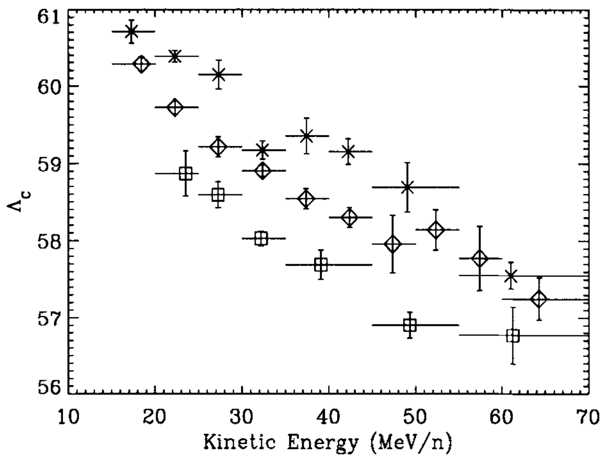


FIG. 3. Measured Λ_C for C (*crosses*), O (*diamonds*), and Si (*squares*) as a function of energy in the 1992 November 2 SEP event.

order to plot the data vs rigidity, both the existence and the magnitude of the offset are independent of the assumed Q for linear fits to any single element. The offset corresponds to free access of particles at $\Lambda \geq 65°$, which is similar to the observed boundary of the electron polar cap (14) and agrees well with other lower rigidity cutoff measurements in these same SEP events (15). The derived cutoff–rigidity relations based on these assumptions are:

$$\cos^4 \Lambda_C = 0.0250 + 8.57 \times 10^{-5} R_C \text{ for the first SEP event, if } Q(C) = +5.7$$

$$\cos^4 \Lambda_C = 0.0233 + 9.32 \times 10^{-5} R_C \text{ for the first SEP event, if } Q(C) = +6$$

$$\cos^4 \Lambda_C = 0.0298 + 7.06 \times 10^{-5} R_C \text{ for the second SEP event, if } Q(C) = +5.7$$

$$\cos^4 \Lambda_C = 0.0278 + 7.81 \times 10^{-5} R_C \text{ for the second SEP event, if } Q(C) = +6$$

where R_C is in units of MV. With the two limiting C charge states used to bound the allowed variations in the cutoff–rigidity relation, the set of measured cutoffs and energies can now be used to obtain the mean charge states for other elements.

The resulting mean values for Q are listed in Table 1, with uncertainties typically dominated by the systematic uncertainty in the C ionic charge state. These Q values are consistent with those measured at low energies (2), and are clearly less than fully stripped for all elements examined heavier than C, as illustrated in Figure 5. Note that the close agreement between our results and those of Luhn et al. (2) 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., (16)). The values are similar to those expected from equilibrium calculations of collisional ionization for a plasma at 2×10^6 K (17,18), as shown in Figures 5 and 6. The inferred source temperatures for Ne and perhaps

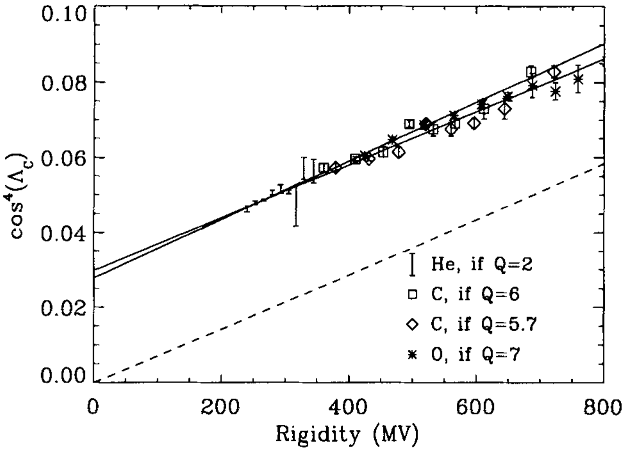


FIG. 4. Plot of $\cos^4(\Lambda_C)$ vs rigidity for He (*vertical bars*), C (*squares, diamonds*), and O (*asterisks*) for the 1992 November 2 SEP event, assuming the charge states indicated. Limiting cases for the cutoff–rigidity relation adopted here are the fits to the He and C data (*solid lines*), one for each plotted C charge state, and are compared with the Störmer model (13) western cutoff (*dashed curve*).

TABLE 1. SEP ionic charge states and corresponding source temperatures.

			SEP Event #1 (1992 Oct 30)		SEP Event #2 (1992 Nov 2)	
	Z	E (MeV/n)	$< Q >$	T (MK)[a]	$< Q >$	T (MK)[a]
He	2	8 – 16	2.00[b]		2.00[b]	
C	6	15 – 65	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
O	8	17 – 70	6.93 ± 0.20	2.37 ± 0.22	6.99 ± 0.22	2.45 ± 0.25
Ne	10	19 – 65	8.68 ± 0.30	3.91 ± 0.64	8.47 ± 0.28	3.39 ± 0.66
Na	11	19 – 48	8.50 ± 0.39	1.09 ± 0.20	9.36 ± 0.37	3.67 ± 1.65
Mg	12	20 – 65	10.35 ± 0.40	4.63 ± 2.32	10.29 ± 0.35	4.38 ± 2.18
Al	13	21 – 48	11.63 ± 0.73	7.53 ± 4.96	10.66 ± 0.68	4.17 ± 2.69
Si	14	22 – 65	10.57 ± 0.39	1.76 ± 0.11	10.51 ± 0.40	1.75 ± 0.12
S	16	24 – 50	10.82 ± 0.81	2.02 ± 0.26	10.84 ± 0.44	2.04 ± 0.14
Ar	18	25 – 35			10.08 ± 0.91	1.67 ± 0.39
Ca	20	26 – 50			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
Ni	28	31 – 45			12.62 ± 1.30	2.04 ± 0.22

[a] Based on equilibrium calculations of collisional ionization (17,18)
[b] Used in normalization

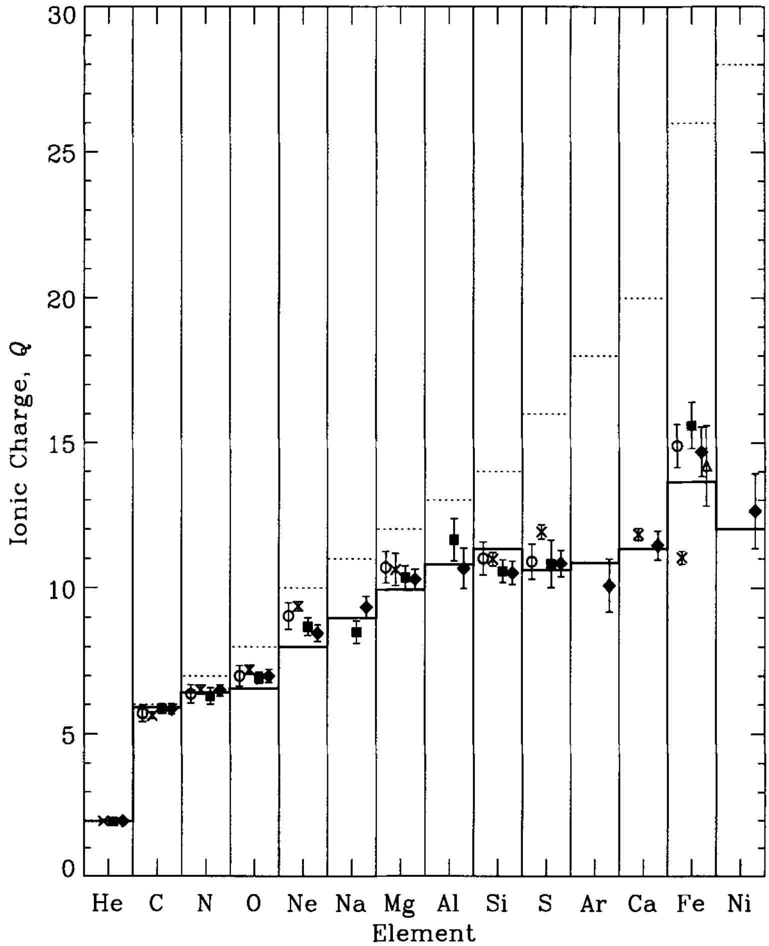


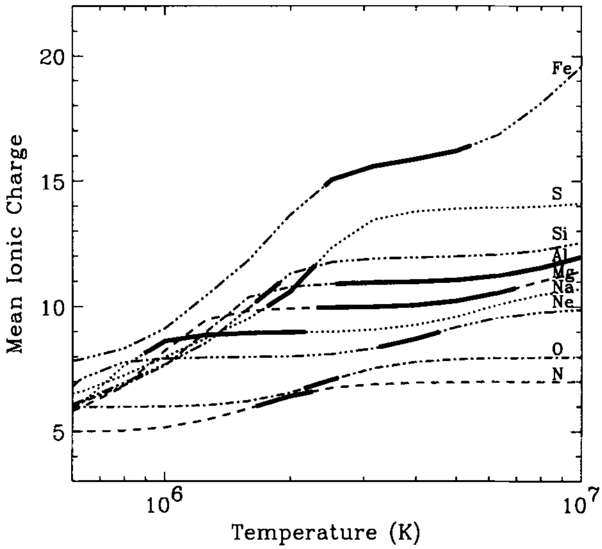
FIG. 5. Mean measured values of Q for the indicated elements, from the 1992 October 30 SEP event (*squares*) and 1992 November 2 SEP event (*diamonds*) at $\sim 15-70$ MeV nucleon^{-1}, from the Luhn et al. (2) 12–flare average at $\sim 0.3-3$ MeV nucleon^{-1} (*circles*) with 5% systematic uncertainty, from Mason et al. (15) at $\sim 0.5-5$ MeV nucleon^{-1} (*crosses*), and from Tylka et al. (21) at $\sim 200-600$ MeV nucleon^{-1} (*triangle*). The heavy solid line shows the value of Q expected for a 2×10^6 K source plasma (17,18), while the dashed line marks the fully stripped ($Q = Z$) value of Q for each element.

Mg are higher than for the other elements, confirming earlier findings (2), and suggesting that an additional mechanism such as photoionization due to flare X–rays (3) may play an important role, that equilibrium temperature calculations (particularly for 2–electron ions) may need refining, or that the assumption of equilibrium is not valid. As seen in Figure 6, some elements not measured by Luhn et al. (2), such as Na and Al, have deduced temperatures with large uncertainties since 2–electron ions exhibit a broad, relatively flat plateau where little change is expected in Q with temperature (18), while others such as Ar, Ca, and Ni are consistent with $\sim 2 \times 10^6$ K. Note also that calculations indicate that at 2×10^6 K, the charge state for Ni should actually be less than that for Fe, consistent with our measurements. This temperature indicates that the source material for large SEP events is more likely to be ambient coronal material, rather than the hotter flare plasma.

Similar measurements during these same SEP events from other instruments on *SAMPEX* at the lower energies of $0.5 - 5$ MeV nucleon^{-1} (15) and at $10 - 100$ MeV nucleon^{-1} (19) are generally in close agreement with both the MAST and Luhn et al. (2) charge state values, with the notable exception of Fe, for which Mason et al. (15) 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. Recent studies (20) find that R_C is 5% below the Störmer western cutoff at $\cos^4(\Lambda_C) \sim 0.25$, corresponding to rigidities well beyond those of our Fe data. 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 as this new line is essentially identical to the cutoff–rigidity relation we derive for the second SEP event. The MAST data do not appear to support a Q as low as 11 at > 30 MeV nucleon^{-1}, and Fe measurements in other SEP events at $\sim 200 - 600$ MeV nucleon^{-1} using passive nuclear track detectors (21) yield a value of Q of 14.2 ± 1.4, similar to that obtained from MAST.

It may be possible to account for this discrepancy if there is a mixture of charge states in the source plasma, and if those with larger Q/M ratios are preferentially accelerated to higher energies than those with lower Q/M. This would appear to be consistent with the fact that these are Fe–poor events (relative to the coronal Fe/O ratio) at the MAST energies (since Q/M is ~ 0.27 for Fe and ~ 0.44 for O), yet apparently Fe–rich at lower energies (15). We find an Fe/O ratio of 0.031 in the first event and 0.071 in the second, compared with the coronal value of 0.172 (22), while the published low energy spectra (15) yield a value of ~ 0.4. 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 the other *SAMPEX* investigators to better determine any possible energy dependence and its significance.

Also in progress are studies of the path length required to produce little or no additional stripping for most elements during acceleration to these higher energies. Preliminary calculations suggest that it may be possible to place



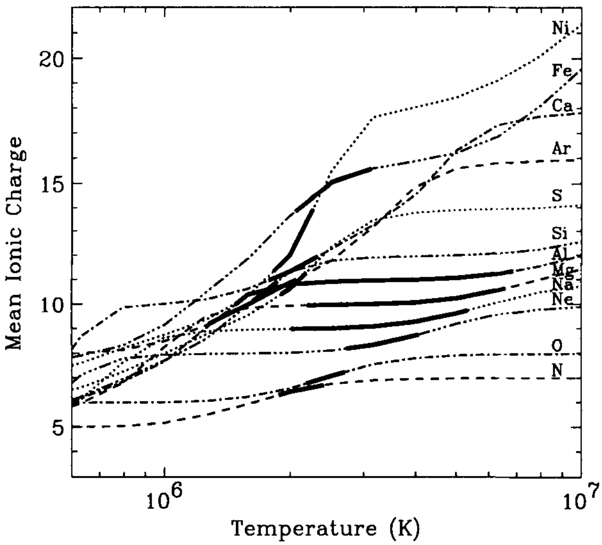


FIG. 6. Expected dependence of mean ionic charge on temperature, based on calculations of collisional ionization (17,18), for the indicated elements, with different line styles serving merely to help separate the various elements. Heavy line segments highlight those portions of the curves consistent with MAST measurements of Q in the 1992 October 30 (*top*) and November 2 (*bottom*) SEP events.

an upper limit on the amount of material SEPs encounter of as much as a factor of 50 lower than the 30 mg cm^{-2} upper limit obtained from studies of the nuclear fragmentation isotopes of H and He (23), which again points to acceleration in a low density region.

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

REFERENCES

1. Kahler, S. W., *Ann. Rev. Astron. and Astrophys.* **30**, 113 (1992).
2. Luhn, A., et al., *Proc. 19th Internat. Cosmic Ray Conf. (LaJolla)* **4**, 241 (1985).
3. Mullan, D. J. and Waldron, W. L., *Astrophys. J.* **308**, L21 (1986).
4. Doschek, G. A., *Phil. Trans. R. Soc. Lond. A* **336**, 451 (1991).
5. Leske, R. A., Cummings, J. R., Mewaldt, R. A., Stone, E. C., and von Rosenvinge, T. T., *Astrophys. J.* **452**, L149 (1995).
6. Cook, W. R., et al., *IEEE Trans. Geoscience Remote Sensing* **31**, 557 (1993).
7. Roederer, J. G., *Dynamics of Geomagnetically Trapped Radiation*, New York: Springer (1970).
8. Fanselow, J. L. and Stone, E. C., *J. Geophys. Res.* **77**, 3999 (1972).
9. Seo, E. S., Ormes, J. F., Streitmatter, R. E., Stochaj, S. J., Jones, W. V., Stephens, S. A., and Bowen, T., *Astrophys. J.* **378**, 763 (1991).
10. Shea, M. A. and Smart, D. F., *Proc. 18th Internat. Cosmic Ray Conf. (Bangalore)* **3**, 415 (1983).
11. Boberg, P. R., Tylka, A. J., Adams, J. H., Jr., Flückiger, E. O., and Kobel, E., *Geophys. Res. Letters* **22**, 1133 (1995).
12. Gloeckler, G., et al., *J. Geophys. Res.* **99**, 17637 (1994).
13. Smart, D. F. and Shea, M. A., *Proc. 23th Internat. Cosmic Ray Conf. (Calgary)* **3**, 781 (1993).
14. Evans, L. C. and Stone, E. C., *J. Geophys. Res.* **77**, 5580 (1972).
15. Mason, G. M., Mazur, J. E., Looper, M. D., and Mewaldt, R. A., *Astrophys. J.* **452**, 901 (1995).
16. Breneman, H. H. and Stone, E. C., *Astrophys. J.* **299**, L57 (1985).
17. Arnaud, M. and Raymond, J., *Astrophys. J.* **398**, 394 (1992).
18. Arnaud, M. and Rothenflug, R., *Astron. and Astrophys. Suppl.* **60**, 425 (1985).
19. Oetliker, M., Klecker, B., Hovestadt, D., Scholer, M., Blake, J. B., Looper, M., and Mewaldt, R. A., *Proc. 24th Internat. Cosmic Ray Conf. (Rome)* **4**, 470 (1995).
20. Selesnick, R. S., Cummings, A. C., Cummings, J. R., Mewaldt, R. A., Stone, E. C., and von Rosenvinge, T. T., *J. Geophys. Res.* **100**, 9503 (1995).
21. Tylka, A. J., Boberg, P. R., Adams, J. H., Jr., Beahm, L. P., Dietrich, W. F., and Kleis, T., *Astrophys. J.* **444**, L109 (1995).
22. Garrard, T. L. and Stone, E. C., *Proc. 23rd Internat. Cosmic Ray Conf. (Calgary)* **3**, 384 (1993).
23. Mewaldt, R. A. and Stone, E. C., *Proc. 18th Internat. Cosmic Ray Conf. (Bangalore)* **4**, 52 (1983).