1995ApJ...444L.109T

THE ASTROPHYSICAL JOURNAL, 444:L109–L113, 1995 May 10
© 1995. The American Astronomical Society. All rights reserved. Printed in U.S.A.

# THE MEAN IONIC CHARGE STATE OF SOLAR ENERGETIC Fe IONS ABOVE 200 MeV PER NUCLEON

A. J. TYLKA,[1] P. R. BOBERG,[2] J. H. ADAMS, JR., AND L. P. BEAHM
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375-5352
W. F. DIETRICH
Laboratory for Astrophysics and Space Research, Enrico Fermi Institute, University of Chicago, Chicago, IL 60637
AND
T. KLEIS
CSI Institute, George Mason University, Fairfax, VA 22030-4444
*Received 1995 February 2; accepted 1995 February 23*

## ABSTRACT

We have analyzed the geomagnetic transmission of solar energetic Fe ions at ~200–600 MeV per nucleon during the great solar energetic particle (SEP) events of 1989 September–October. By comparing fluences from the Chicago charged-particle telescope on *IMP-8* in interplanetary space and from NRL's Heavy Ions in Space (HIIS) experiment aboard the *Long Duration Exposure Facility* (*LDEF*) in low-Earth orbit, we obtain a mean ionic charge $\langle Q \rangle = 14.2 \pm 1.4$. This result is significantly lower than $\langle Q \rangle$ observed at ~1 MeV per nucleon in impulsive, $^3$He-rich SEP events, indicating that neither acceleration at the flare site nor flare-heated plasma significantly contributes to the high-energy Fe ions we observe. But it agrees well with the $\langle Q \rangle$ observed in gradual SEP events at ~1 MeV per nucleon, in which ions are accelerated by shocks driven by fast coronal mass ejections, and hence shows that particles are accelerated to very high energies in this way. We also note apparent differences between solar wind and SEP charge state distributions, which may favor a coronal (rather than solar wind) seed population or may suggest additional ionization in the ambient shock-region plasma.

*Subject headings:* acceleration of particles — solar wind — Sun: flares — Sun: particle emission

## 1. INTRODUCTION

Ionic charge states provide important clues about the source population, acceleration mechanism, and propagation history of energetic particles. For solar energetic particles (SEPs), measurements of the mean ionic charge state ($\langle Q \rangle$) of Fe, along with studies of SEP composition and associated flare and plasma phenomena, helped to elucidate two distinct acceleration mechanisms (Reames 1992a, 1993; Kahler 1992; Gosling 1993).

In so-called "impulsive" SEP events, $\langle Q \rangle = 20.5 \pm 1.2$ for Fe ions at ~1 MeV per nucleon (Luhn et al. 1987). Impulsive events (Reames 1990a) are also characterized by greatly enhanced $e/p$ and $^3$He/$^4$He ratios (Hsieh & Simpson 1970), heavy-ion enrichments (Mason et al. 1986), gamma-ray emission, typical durations of a few hours, and associated solar flares clustered at western heliolongitudes which are magnetically well-connected to the observer (Cane, Reames, & Von Rosenvinge 1991). These features suggest that particle acceleration occurs in a localized region, near the flare site, where additional heating of the source plasma (Luhn et al. 1987; Luhn & Hovestadt 1987) or further stripping takes place (Miller & Viñas 1993; Reames, Meyer, & Von Rosenvinge 1994).

In "gradual" SEP events, fast coronal mass ejections (CMEs) drive shocks, which propagate through the corona and interplanetary medium and accelerate particles from the ambient plasma. Averaging over 12 such events, Luhn et al. (1987) reported $\langle Q \rangle = 14.1 \pm 0.2$ for Fe ions at ~1 MeV per nucleon, corresponding to an inferred plasma temperature of ~2 MK, typical of coronal material (Arnaud & Raymond 1992). The heavy-ion abundances in these events also reflect coronal abundances, at least at low energies (Meyer 1985a, b; Breneman & Stone 1985; Reames 1992b; Mazur et al. 1993). These events often have large fluences and hard spectra, since particle acceleration can persist for days as the CME and shock expand through a large part of the inner heliosphere (Reames 1990b).

Composite events, in which both acceleration mechanisms operate, have also been observed (Mason et al. 1989; Debrunner, Lockwood, & Ryan 1992).

Since higher energies generally require longer residence times in the acceleration region, high-energy charge state measurements offer potentially stringent constraints on models of SEP acceleration. In this *Letter* we report first measurements of the mean ionic charge of SEP Fe at ~200–600 MeV per nucleon. We determine $\langle Q \rangle$ by analyzing the geomagnetic transmission of these ions, as deduced by comparing fluences from the HIIS experiment in low-Earth orbit and from the University of Chicago/*IMP-8* charged-particle telescope in interplanetary space. These observations are dominated by the SEP events of 1989 September–October (Reeves et al. 1992; Belian et al. 1992; Sauer 1993), which produced ground-level neutron-monitor enhancements (Mathews & Venkatesan 1990) and some of the largest SEP fluences ever observed (Shea et al. 1993). Preliminary versions of this work have been reported previously (Adams et al. 1991a, 1993; Tylka et al. 1995a).

## 2. HEAVY IONS IN SPACE (HIIS) OBSERVATIONS

NASA's *Long Duration Exposure Facility* (*LDEF*; Kinard & Martin 1991) was deployed in a 28°.5, 476 km circular orbit

[1] tylka@crs1.nrl.navy.mil.
[2] National Research Council Post-Doctoral Research Associate.



© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...444L.109T



on 1984 April 7 and retrieved at 332 km on 1990 January 12. This orbit carried *LDEF* through Earth's inner magnetosphere at $L \lesssim 1.7$. *LDEF* was 3-axis stabilized, with NRL's Heavy Ions in Space (HIIS) experiment mounted on the space-facing end. HIIS had an unobstructed view and efficient particle detection down to zenith angles of $\sim 70°$. HIIS used large, thick stacks of plastic track detectors, with a total vertical depth of $\sim 12$ g cm$^{-2}$ and a combined geometry factor of $\sim 2.0$ m$^2$ sr. The HIIS detectors were passive, with no direct information on when ions were collected.

A detailed description of HIIS has been published elsewhere (Adams et al. 1991b; Tylka et al. 1995a). These data come from one of the eight HIIS modules. A small subsample of the particle tracks was used to calibrate the detectors (Tylka et al. 1995a). Applying this internal calibration, we fit the entire dataset and obtained the histogram in Figure 1. A Gaussian fit to the Fe peak yields standard deviation $\sigma = 0.43 \pm 0.04$ charge unit.

Figure 2 shows the HIIS mission-averaged Fe flux measurements. Our fluxes are in good agreement with those from other *LDEF* experiments (Beaujean et al. 1995; Wiegel et al. 1995). The Galactic cosmic ray (GCR) curves in Figure 2 are absolute predictions, averaged over solar-cycle variation during the *LDEF* mission (Nymmik et al. 1992) and convolved with two different calculations of the geomagnetic transmission function (GTF; Adams et al. 1991c) for the *LDEF* orbit. The GTF for the dashed curve was calculated from the Shea & Smart (1989) cutoff grid, which is based on trajectory-tracings through the International Geomagnetic Reference Field (IGRF). The GTF for the solid GCR curve was calculated with a program (Flückiger et al. 1991) that traced trajectories through both the IGRF and the Tsyganenko magnetospheric field model (Tsyganenko 1989), which we modified to describe very large geomagnetic disturbances (Boberg et al. 1995). We calculated GTFs for 10 different levels of geomagnetic activity (corresponding to $Kp = 0$–$9$) and combined them in a weighted average, with weights determined by the record of geomagnetic activity.

GCRs can explain the HIIS Fe flux above $\sim 800$ MeV per nucleon but not at lower energies: a fully ionized GCR Fe ion

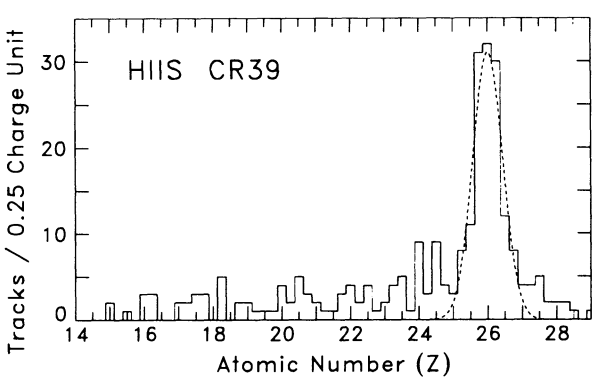


FIG. 1.—Histogram of fitted atomic numbers. These tracks stopped in the HIIS CR39 detectors, which were sealed in 1 atm dry air and provided Fe group measurements at energies above $\sim 160$ MeV per nucleon. Lower-energy ions—not included in this histogram—were located in Lexan detectors exposed in vacuum, which yielded poorer resolution (Kleis et al. 1995). The dashed curve shows a Gaussian fit to the Fe peak with standard deviation $\sigma = 0.43$. This histogram is uncorrected for $Z$-dependent acceptance effects. Our scanning method generally does not find ions at $Z < 14$, and the acceptance increases gradually between $Z = 14$ and $Z = 20$. At larger $Z$, the acceptance is constant to within $\sim 15\%$.

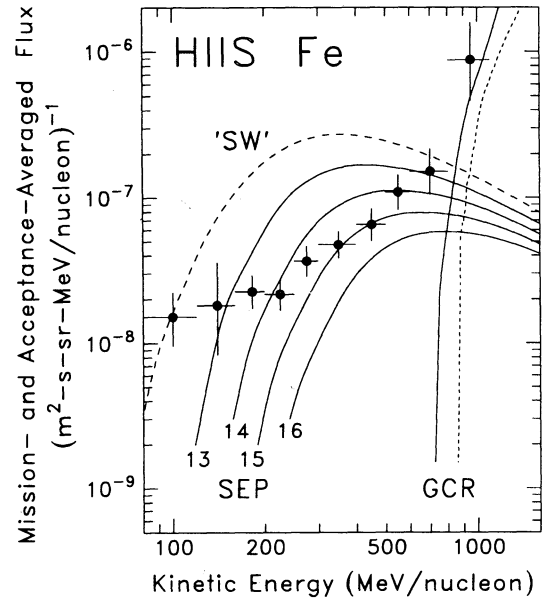


FIG. 2.—HIIS mission- and acceptance-averaged Fe-group fluxes, at the surface of LDEF, after correction for energy-loss and fragmentation. The data points above 160 MeV per nucleon (from CR39 detectors) are for $25 \lesssim Z \lesssim 27$; the lower energy data points (from Lexan detectors) are for $Z \gtrsim 21$ (Kleis et al. 1995). Data points below 80 MeV per nucleon, in which geomagnetically trapped ions dominate, are not shown. Error bars include both statistical and systematic errors (typically $\sim 10\%$). The curves labeled GCR are absolute predictions of the expected flux of fully ionized Galactic cosmic-ray Fe, propagated to the LDEF orbit with two different calculations of the geomagnetic transmission function (see text). The SEP curves correspond to different assumed values of the mean ionic charge ($\langle Q \rangle$), as discussed in the text. The curve labeled "SW" shows the expected flux at HIIS if SEPs had the same charge state distribution as typically observed in the solar wind.

at $\sim 500$ MeV per nucleon requires a geomagnetic storm with $Dst \lesssim -300$ nT in order to reach the *LDEF* orbit. During the *LDEF* mission, there were only 11 hours during which $Dst < -300$ nT. The GCR fluence collected during these 11 hours falls at least 3 orders of magnitude below the observed fluence.

Because HIIS provided no timing information, we must use other features of the data to identify or eliminate other possible source(s) of the ions. For example, the highly anisotropic distribution of arrival directions (Tylka et al. 1995a) is centered about the direction of lowest cutoff and consistent with the geomagnetic transmission of a steeply falling interplanetary spectrum. But the distribution is dramatically different from the south-easterly arrival directions of geomagnetically trapped ions in HIIS (Kleis et al. 1995).

Composition provides another indication of origin. Figure 3 shows the sub-Fe to Fe ratio at various depths in the detector stack. The curves in Figure 3 were calculated by first adjusting the incident spectrum of the hypothetical source (SEPs, GCRs, or GCR albedo) to match the Fe spectrum[3] in Figure 2. A nuclear transport code then propagated each hypothetical source to various depths in the detector. The HIIS composition is consistent with the SEP curve, which corresponds to an incident sub-Fe to Fe ratio of $0.032 \pm 0.014$, as observed on *IMP-8* at $\sim 100$–$400$ MeV per nucleon during the 1989

[3] For GCRs and albedo, this matching required unrealistically large cutoff suppressions ($Dst \sim -600$ nT) or long pathlengths ($\gtrsim 20$ g cm$^{-2}$) through air, respectively. For SEPs, the observed Fe spectrum required partially ionized charge states, as discussed in § 5.

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...444L.109T



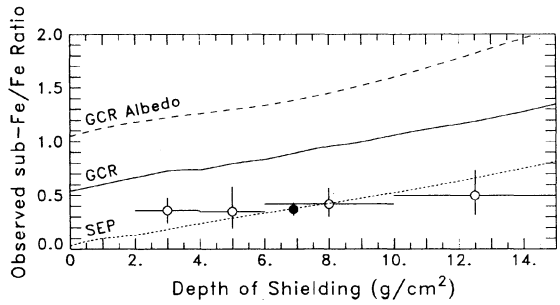


FIG. 3.—Sub-Fe to Fe ratio [defined as $\Sigma(21 < Z < 25)/\Sigma(Z \geq 25)$] as observed at various depths in the detector stack. The open circles are for subsets of the data shown in Fig. 1. The filled circle is for the complete dataset, with abscissa at the mean shielding depth. The data points correspond to stopping Fe ions with incident energies of ~185–650 MeV per nucleon. Small corrections (~5%) have been applied to the measurements, to account for the weak $Z$-dependence of the detector acceptance. The curves show the expected composition from various sources, after taking into account fragmentation in the detector.

September–October events. But it is inconsistent with the composition expected for GCRs or albedo.[4]

### 3. INTERPLANETARY SEP OBSERVATIONS

The University of Chicago charged-particle telescope on *IMP-8* (Garcia-Munoz, Mason, & Simpson 1975) monitored SEP events throughout the *LDEF* mission. Figure 4 shows events of 1989 September–October, which accounted for nearly all of the high-energy (>100 MeV per nucleon) SEP Fe fluence during the *LDEF* mission. Three smaller events (1989 August 16, 17, and October 22) provided an additional ~4%, and the combined high-energy Fe fluence from all other SEP events was no more than 1%. Systematic uncertainties in the Chicago/*IMP-8* fluences are typically 10%–20%, except for the 1989 October 20 event, which was produced by the passage of a powerful interplanetary shock. In this case, problems associated with very high rates in the electronic detectors left a factor of 2 systematic uncertainty in the Fe fluence. This systematic uncertainty has been taken into account in all subsequent analysis. Details about the Chicago/*IMP-8* SEP observations are available elsewhere (Dietrich & Chenette 1995).

### 4. GEOMAGNETIC TRANSMISSION

To evaluate geomagnetic transmission from interplanetary space to the *LDEF* orbit, we used the trajectory-tracing program described in Boberg et al. (1995). The program calculated a separate rigidity-dependent GTF for each SEP event, averaged over HIIS lookout directions and locations along the actual *LDEF* orbital path. To account for changes in the level of cutoff suppression, the program varied the effective ring current parameter to match the hourly *Dst*-values. To account for variation in the exomagnetospheric source flux, a separate GTF was calculated for each 3 hour orbital segment. These GTFs were then combined in a weighted average, with weights determined by the observed time-lines of various interplanetary fluences, all of which yielded very similar results.

Calculating geomagnetic transmission is particularly challenging for 1989 October: the peak particle flux on 1989 October 20 coincided with $Dst = -202$ nT, and an even larger disturbance ($Dst = -268$ nT) occurred about a day later, during the declining phase of the particle event. To validate our GTF calculations we undertook two additional studies. First, we analyzed the geomagnetic transmission of solar energetic protons during these events by comparing fluxes from *NOAA-10* (98°.5, ~800 km orbit) and *GOES-7* (geosynchronous orbit). The trajectory-tracing program reproduced the observed *NOAA-10* 3 hour orbit-averaged transmissions to within ~15% (Boberg et al. 1995). Second, we repeated our GTF calculations using the model of Flückiger, Smart, & Shea (1986, hereafter FSS), which provides an empirical parameterization of cutoff-suppression in terms of *Dst*, valid at mid- and low-latitudes, and hence directly applicable to cutoff rigidities sampled by *LDEF*. These FSS calculations tended to show somewhat less cutoff suppression than the trajectory tracings, but nevertheless gave quite comparable results (Adams et al. 1993).

### 5. RESULTS

Using the event-averaged GFTs and the power-law fits in Figure 4, we calculated the combined fluence in HIIS from all events, leaving $\langle Q \rangle$ (the mean ionic charge *outside* the magnetosphere) and the width of the charge state distribution

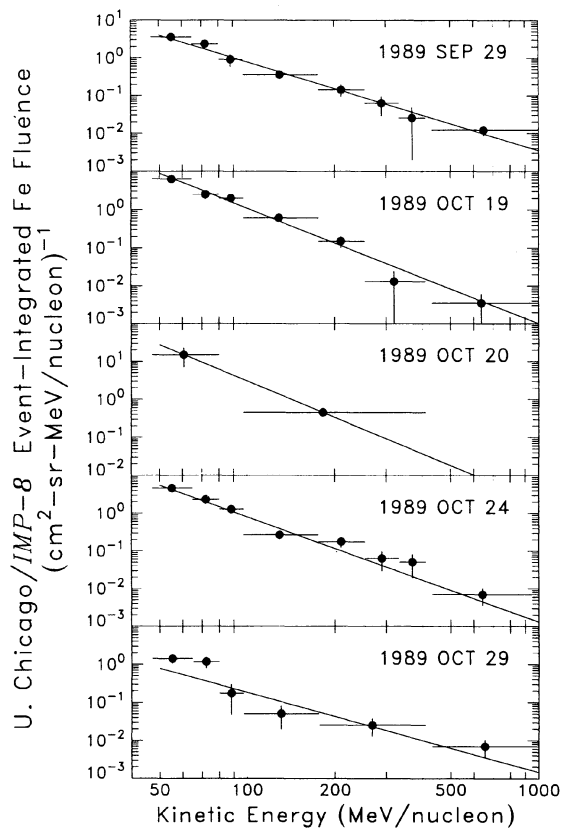


FIG. 4.—Event-integrated fluence for SEP events during the *LDEF* mission from the University of Chicago charged-particle telescope on *IMP-8*. Error bars are statistical only. Power laws give good fits, at least above ~80 MeV per nucleon.

[4] Albedo can also be rejected as the source of the observed ions on the basis of total fluence. See Adams et al. (1991a).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...444L.109T



(see below) as free parameters. We neglected possible event-to-event variability and energy-dependence in the charge state distribution, so that our $\langle Q \rangle$-value is effectively an ensemble average. Typical results are shown in Figure 2. Fine-tuning the charge state distribution or allowing slight event-to-event variation improves the fit to the spectrum, but clearly the HIIS fluxes require $\langle Q \rangle \sim 14$, at least above $\sim$200 MeV per nucleon.

Previous SEP results at $\sim$1 MeV per nucleon provide little guidance about the charge state distribution, since electrostatic-deflection measurements of individual ions were dominated by large errors (Luhn et al. 1985, 1987). Isothermal calculations for coronal plasmas (Arnaud & Raymond 1992; Shull & Van Steenberg 1982) are probably not directly applicable to SEPs. Solar wind (SW) charge state distributions are perhaps most relevant here, since the solar wind may provide seed particles for SEPs (Cane et al. 1991). SW distributions are variable (Ipavich et al. 1992) and highly non-thermal (except for cool coronal-hole flows; Von Steiger, Geiss, & Gloecker 1995). Generally, SW distributions are relatively flat (except for enhancements in the Ne-like $Fe^{+16}$ ion in hotter flows) and broad, with rms widths of $\sim$2–3 charge units and $\langle Q \rangle \sim 10$–13.

In our calculations we therefore used (nearly) flat distributions, with rms width $\sigma_{rms}$ varying between $\sim$0.3–4 charge units. Our fit procedure simultaneously varied both $\langle Q \rangle$ and $\sigma_{rms}$. Our best fit to the data above 200 MeV per nucleon gave $\sigma_{rms} \sim 2.5$ and $\langle Q \rangle = 14.2 \pm 1.4$. The error on $\langle Q \rangle$ comprises both statistical and systematic uncertainties, added in quadrature. Our error analysis included uncertainties in the HIIS data and in the *IMP-8* fluences and spectral indices. The result is dominated, however, by systematic error.

The largest source of systematic error is our lack of knowledge about the shape of the charge state distribution. To estimate this uncertainty, we found the best-fit value of $\langle Q \rangle$ for various $\sigma_{rms}$-values. We also did calculations using theoretical coronal distributions (Arnaud & Raymond 1992; Shull & Van Steenberg 1982). From these variations, we estimated a contribution of $\sim$1.0 charge unit to the systematic uncertainty in $\langle Q \rangle$.

The second potential source of systematic uncertainty is the geomagnetic transmission. To bracket this uncertainty, we considered two extreme GTF calculations. One calculation repeated the trajectory tracings, but with *Dst* fixed at $-268$ nT, the largest value in 1989 October. The other calculation used the Shea & Smart (1989) grid, which takes no account of magnetospheric currents or cutoff suppression. These two calculations changed the best-fit $\langle Q \rangle$ by $\sim \pm 1.5$ charge units, respectively. This range clearly overestimates the actual systematic uncertainty. Based on other studies (including more modest levels of cutoff suppression and the FSS model), we believe that a realistic estimate of this contribution to the systematic uncertainty in $\langle Q \rangle$ is $\pm 0.9$ charge unit.

The SEP curves in Figure 2 do not follow the observed spectrum below $\sim$150 MeV per nucleon. The origin of these ions is unclear, since we were not able to measure the sub-Fe to Fe ratio at these energies (Tylka et al. 1995b). We can match the observed fluence at $\sim$100–150 MeV per nucleon by allowing $\sim$0.5% of the SEP Fe to have $6 \leq Q \leq 9$. These charge states are present in the solar wind at $\sim$1%–10% levels (Geiss et al. 1994; Ipavich et al. 1992) and may also be present in SEPs.

## 6. DISCUSSION

Our result is inconsistent with $\langle Q \rangle = 20.5 \pm 1.2$, as observed in impulsive events, and hence shows that neither acceleration at the flare site nor ions from flare-heated plasma significantly contribute to the high-energy Fe we observe. Our result is in good agreement with $\langle Q \rangle = 14.1 \pm 0.2$ observed in gradual events at $\sim$1 MeV per nucleon,[5] confirming that shock acceleration in the corona or interplanetary medium does produce very high-energy particles. Our result is in qualitative agreement with Kahler (1994), who correlated SEP time lines with CME expansion profiles (including those of 1989 September 29 and October 24) to show that SEP acceleration peaks when the CME has reached $\gtrsim$5–15 solar radii.

Our result also underpins studies of systematic patterns in SEP elemental abundances, which assumed that $\langle Q \rangle$ observed at $\sim$1 MeV per nucleon persists to higher energies (Breneman & Stone 1985; Cane et al. 1991; Mazur et al. 1993). High-energy partially ionized charge states should also be reflected in rigidity-dependent propagation of SEPs through the interplanetary medium (Dietrich 1995).

As shown in Figure 2, SEPs with the same charge state distribution as typically observed for SW ions (with $\langle Q \rangle \sim 11.8$; Von Steiger et al. 1995) would have produced fluences inconsistent with the HIIS data. Other SW distributions (Ipavich et al. 1992) gave similar results. Relative to the SW, SEPs appear to be depleted in Fe ions with $Q \leq 10$. This may suggest either a coronal (rather than SW) seed population or perhaps additional ionization near the shock. Coordinated SW and SEP observations may thus offer new insights into SEP injection and acceleration processes.

We thank Bill Kinard and staff members of the *LDEF* Project Office at NASA/Langley for their work to ensure the success of the *LDEF* mission. We thank US Space Command (J3SOS) for the *LDEF* orbital elements. We thank Erwin Flückiger and E. Kobel (for making their trajectory tracing program available to us), Peggy Shea and Don Smart (for very helpful discussions of geomagnetic cutoff calculations), and Toni Galvin and Rudi von Steiger (for discussions of solar wind data). We also thank our student microscopists, Lorie Benning, Rich Witt, and Kenny Zee. This work has been supported by the Office of Naval Research, NASA contract W-18409 (NRL), and NASA grant NAG 5-706 (University of Chicago).

[5] Preliminary results from *SAMPEX* show similar charge states at $\sim$15–70 MeV per nucleon (Leske et al. 1994) in two SEP events in late 1992.

## REFERENCES

Adams, J. H., Jr., Beahm, L. P., & Tylka, A. J. 1991a, Proc. 22d Internat. Cosmic-Ray Conf. (Dublin), 1, 619
———. 1991b, in Proc. First *LDEF* Post-Retrieval Symp. Vol. 1, ed. A. S. Levine (NASA CP-3134), 377
———. 1991c, ApJ, 377, 292
Adams, J. H., Jr., Beahm, L. P., Boberg, P. R., Kleis, T., & Tylka, A. J. 1993, Proc. 23d Internat. Cosmic-Ray Conf. (Calgary), 3, 374
Arnaud, M., & Raymond, J. 1992, ApJ, 398, 394
Beaujean, R., Barz, S., Jonathal, D., & Enge, W. 1995, Adv. Space Res., in press
Belian, R. D., Gisler, G. R., Cayton, T., & Christensen, R. 1992, J. Geophys. Res., 97, 16897
Boberg, P. R., Tylka, A. J., Adams, J. H. Jr., Flückiger, E. O., & Kobel, E. 1995, Geophys. Res. Lett., in press
Breneman, H., & Stone, E. C. 1985, ApJ, 299, L57

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...444L.109T



Cane, H. V., Reames, D. V., & Von Rosenvinge, T. T. 1991, ApJ, 373, 675
Debrunner, H., Lockwood, J. A., & Ryan, J. M. 1992, ApJ, 387, L51
Dietrich, W. F. 1995, in preparation
Dietrich, W. F., & Chenette, D. L. 1995, in preparation
Flückiger, E. O., Kobel, E., Smart, D. F., & Shea, M. A. 1991, Proc. 22d Internat. Cosmic-Ray Conf. (Dublin), 3, 648
Flückiger, E. O., Smart, D. F., & Shea, M. A. 1986, J. Geophys. Res., 91, 7925 (FSS)
Garcia-Munoz, M., Mason, G. M., & Simpson, J. A. 1975, ApJ, 201, L145
Geiss, J., et al. 1994, A&A, 282, 924
Gosling, J. T. 1993, J. Geophys. Res., 98, 18937
Hsieh, K. C., & Simpson, J. A. 1970, ApJ, 162, L191
Ipavich, F. M., Galvin, A. B., Geiss, J., Ogilvie, K. W., & Gliem, F. 1992, in Proc. Solar Wind Seven, Vol. 3, ed. E. Marsch & R. Schwenn, (Oxford: Pergamon) 369
Kahler, S. 1994, ApJ, 428, 837
Kahler, S. W. 1992, ARA&A, 30, 113
Kinard, W. H., & Martin, G. D. 1991, in Proc. First *LDEF* Post-Retrieval Symp., Vol. 1, ed. A. S. Levine (NASA CP-3134), 49
Kleis, T., Tylka, A. J., Boberg, P. R., Adams, J. H., Jr., & Beahm, L. P. 1995, Adv. Space Res., in press
Leske, R. A., et al. 1994, EOS. Trans. A.G.U. (Suppl.), 75, 534
Luhn, A., et al. 1985, Proc. 19th Internat. Cosmic-Ray Conf. (La Jolla), 4, 241
Luhn, A., & Hovestadt, D. 1987, ApJ, 317, 852
Luhn, A., Klecker, B., Hovestadt, D., & Möbius, E. 1987, ApJ, 317, 951
Mason, G. M., Reames, D. V., Klecker, B., Hovestadt, D., & Von Rosenvinge, T. T. 1986, ApJ, 303, 849
Mason, G. M., Ng, C. K., Klecker, B., & Green, G. 1989, ApJ, 339, 529
Mathews, T., & Venkatesan, D. 1990, Nature, 345, 600
Mazur, J. E., Mason, G. M., Klecker, B., & McGuire, R. E. 1993, ApJ, 404, 810
Meyer, J. P. 1985a, ApJS, 57, 151
———. 1985b, ApJS, 57, 173
Miller, J. A., & Viñas, A. F. 1993, ApJ, 412, 386
Nymmik, R. A., Panasyuk, M. I., Pervaja, T. I., & Suslov, A. A. 1992, Nucl. Tracks Radiat. Meas., 20, 427
Reames, D. V. 1990a, ApJS, 73, 235
———. 1990b, ApJ, 358, L63
———. 1992a, in AIP Conf. Proc. 264, Particle Acceleration in Cosmic Plasmas, ed. G. P. Zank & T. K. Gaisser (New York: AIP), 213
———. 1992b, in First SOHO Workshop on Coronal Streamers, Coronal Loops, and Coronal and Solar Wind Composition, ed. V. Domingo (ESA SP-348), 315
———. 1993, Adv. Space Res., 13, (9)331
Reames, D. V., Meyer, J. P., & Von Rosenvinge, T. T. 1994, ApJS, 90, 649
Reeves, G. D., Cayton, T. E., Gary, S. P., & Belian, R. D. 1992, J. Geophys. Res., 97, 6219
Sauer, H. H. 1993, Proc. 23d Internat. Cosmic-Ray Conf. (Calgary), 3, 254
Shea, M. A., & Smart, D. F. 1989, private communication
Shea, M. A., Smart, D. F., Dreschhoff, G. A. M., & Zeller, E. J. 1993, Proc. 23d Internat. Cosmic-Ray Conf. (Calgary), 3, 846
Shull, J. M., & Van Steenberg, M. 1982, ApJS, 48, 95
Tsyganenko, N. A. 1989, Planet. Space Sci., 37, 5
Tylka, A. J., Boberg, P. R., Adams, J. H., Jr., Beahm, L. P., & Kleis, T. 1995a, in Proc. Third LDEF Post-Retrieval Symp., Vol. 1, ed. A. S. Levine (NASA CP-3275), 113
Tylka, A. J., et al. 1995b, ApJ, 438, L83
Von Steiger, R., Geiss, J., & Gloecker, G. 1995, in Cosmic Winds and the Heliosphere, ed. J. R. Jokipii, C. P. Sonnet, & M. S. Giampapa (Tuscon: Univ. Arizona Press), in press
Wiegel, B., et al. 1995, Adv. Space Res., 15, (1)53

© American Astronomical Society • Provided by the NASA Astrophysics Data System

1995ApJ...444L.109T

© American Astronomical Society • Provided by the NASA Astrophysics Data System