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EVIDENCE FOR REMNANT FLARE SUPRATHERMALS IN THE SOURCE POPULATION OF SOLAR ENERGETIC PARTICLES IN THE 2000 BASTILLE DAY EVENT

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ABSTRACT

The energy spectra of Fe in the very large solar energetic particle (SEP) event of 2000 July 14 are strikingly different from those of lighter species. We show that this difference can be explained by shock acceleration from a two-component source population, comprising solar wind suprathermals and a small (~5%) admixture of remnant flare particles, as previously proposed to explain enhanced ^{3}He/^{4}He in some gradual SEP events. Flare remnants can also account for several previously unexplained features of high-energy solar heavy ions as well as important aspects of SEP event-to-event variability. These results offer a new perspective on the enduring controversy over the relative roles of flares and coronal mass ejections (CMEs) in producing SEPs. Flare activity clearly makes a unique and critical contribution to the source population. But the predominate accelerator in large gradual SEP events is the CME-driven shock, and many spectral, compositional, and charge state characteristics of high-energy heavy ions can be understood without invoking other acceleration mechanisms.

Subject headings: acceleration of particles — shock waves — Sun: coronal mass ejections (CMEs) — Sun: flares — Sun: particle emission

1. INTRODUCTION

Suprathermal particles, with speeds several times that of bulk solar wind, are the source population for particles accelerated to high energies by coronal mass ejection (CME)–driven shocks in gradual solar energetic particle (SEP) events. The suprathermal tail of the solar wind (Zurbuchen et al. 2000) is ubiquitous and probably produced by stochastic acceleration processes (Fisk et al. 2000). Recent observations (Mason, Mazur, & Dwyer 1999) suggested that, at least at some times, solar wind suprathermals can be augmented by suprathermals from impulsive SEP events. These suprathermals would have been originally accelerated at a flare site and hence bear distinctive compositional and charge state characteristics. Since suprathermals take several days to move through the inner heliosphere, they constitute a remnant population, replenished nearly continuously by flare activity. A shock would then accelerate particles from both solar wind and flare suprathermals in a more or less democratic fashion.

Mason et al. (1999) posited remnant flare suprathermals to explain measured ^{3}He/^{4}He of a few percent in some large gradual events. ^{3}He is rare in the solar wind, with average ^{3}He/^{4}He $\sim 4 \times 10^{-4}$ (Gloeckler et al. 1999). However, impulsive SEP events often have ^{3}He/^{4}He ~ 1. Thus, a small admixture of flare suprathermals in the source population, on the order of a few percent, would be sufficient. Recent work by Desai et al. (2001) showed correlation between levels of flare activity and ^{3}He enhancements in shock-accelerated particles at 1 AU. Indirect support for the remnant flare hypothesis also comes from the 1998 April 20 SEP event, a large gradual event that marked the end of a period of low solar activity, with no C-, M-, or X-class X-ray flares in the preceding 4 days. Ionic charge states, ^{3}He content, and spectral characteristics of this event are consistent with that of a purely solar wind source population (Tylka et al. 2000, 2001).

In this Letter, we present new evidence for remnant flare suprathermals based on spectral characteristics of high-energy ions in the very large solar event of 2000 July 14. As energy and gyroradius increase, it becomes less probable that a particle can be contained within the shock region. Ellison & Ramaty (1985) suggested that this escape would cause the energy spectra of shock-accelerated particles to roll over more or less exponentially, with *e*-folding energy directly proportional to the ion's charge-to-mass (Q/A) ratio. Thus, information on SEP ionic charge states can be inferred by comparing spectra of various elements, as first demonstrated by Tylka et al. (2000).

The high intensities of the Bastille Day event provide an excellent opportunity to search for spectral signatures of remnant flare suprathermals. The event followed an extended period of high flare activity, with 40 X-ray flares (two X, 17 M, 21 C) in the preceding 4 days. Moreover, the X5.7 flare associated with this event occurred near central meridian (N22°, W07°), far from the footpoint of the Sun-Earth magnetic field line. It is thus unlikely that we saw at Earth particles directly accelerated in this flare. For the same reason, the Bastille Day event is also probably free of complications associated with concurrent acceleration and ion-stripping in the low corona, which affected the well-connected (W63°) event of 1997 November 6 (Reames, Ng, & Tylka 1999; Barghouty & Mewaldt 1999, 2000; Stovpyuk & Ostryakov 2001).

2. OBSERVATIONS AND MODELING

Figure 1 shows heavy-ion spectra in three time intervals, starting 6 hr after the flare and covering the next 20 hr. The top row shows loglinear plots, while the bottom row shows the same spectra again in log-log plots. Data come from the Low-Energy Matrix Telescope (LEMT) in the Energetic Particle Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995) on *Wind* and from the Solar Isotope Spectrometer (SIS; Stone et al. 1998) and the Electron,

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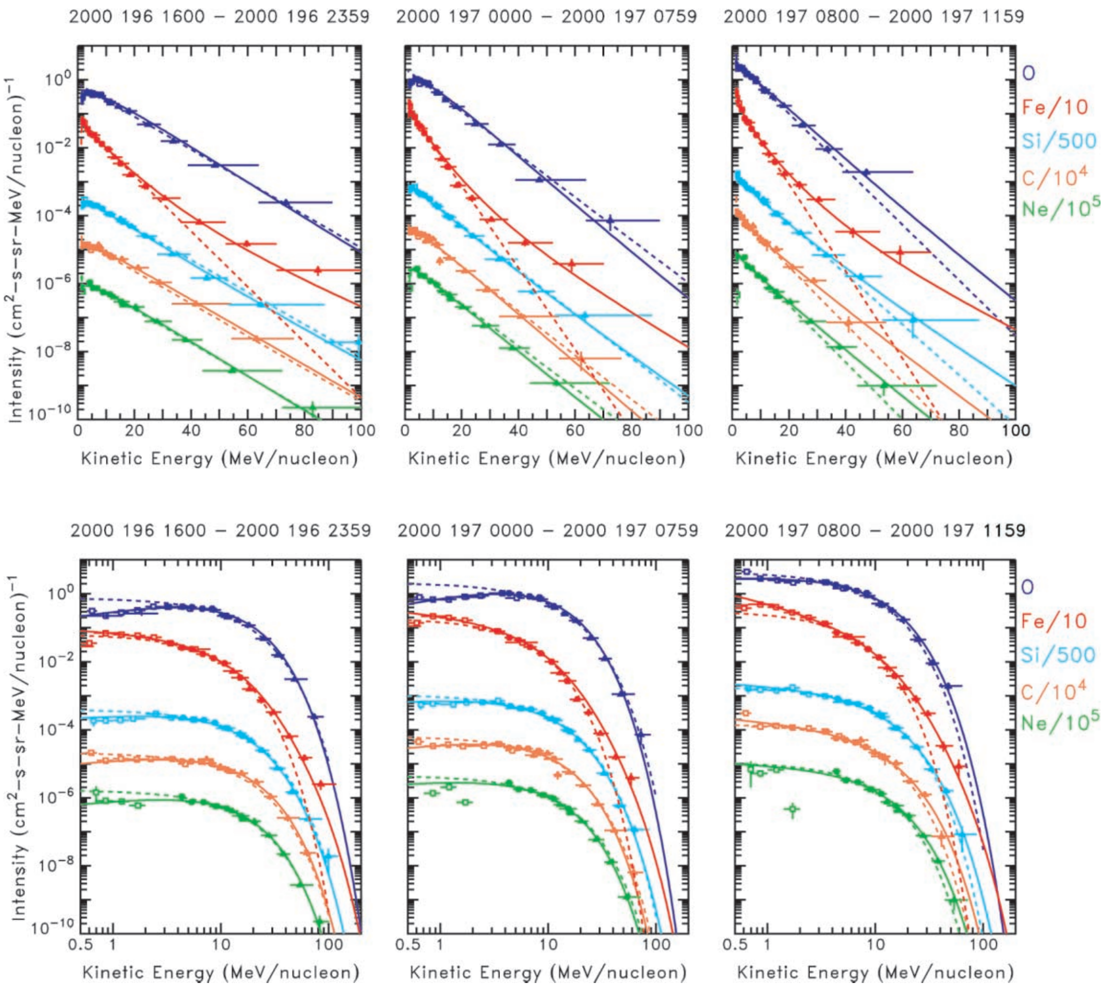

FIG. 1.—Heavy-ion energy spectra in the 2000 July 14 solar particle event. Times are noted at the top. The associated X5.7 flare occurred at ∼10 UT on day 196, and the associated shock arrived at 1 AU at ∼1430 UT on day 197. Species are color-coded and appear in the same order as in the legends at the right. Note the scale factors. Data are from *Wind*/EPACT/LEMT (*filled circles*), *ACE*/EPAM (*open squares*), and *ACE*/SIS (*filled triangles*). Dashed lines are exponential fits to LEMT data only (Reames et al. 2001). Solid curves are model fits, as described in the text.

Proton, and Alpha Monitor (EPAM; Gold et al. 1998) on the *Advanced Composition Explorer* (*ACE*). Modest adjustments (less than a factor of 2) have been used to remove normalization discrepancies among the instruments, without altering the spectral shape reported by any instrument. The adjustments are larger than usual in this event due to very high rates and residual live-time uncertainties

The most striking feature of Figure 1 is the difference between the Fe spectra and those of lighter species. For example, above ∼20 MeV nucleon^{-1}, the Fe spectra are nearly power laws, whereas the other species are clearly exponentials. This spectral difference between Fe and lighter species at high energies has been previously noted (but not explained) in large SEP events in earlier solar cycles (Tylka & Dietrich 1999).

The time intervals in Figure 1 were also examined by Reames, Ng, & Tylka (2001) using only *Wind*/LEMT data at ∼4–20 MeV nucleon^{-1}. The dashed lines are their exponential fits. These fits show that Fe has smaller *e*-folding energies than other species, corresponding to a lower Q/A ratio for Fe, at least at LEMT energies. In fact, Reames et al. (2001) assumed *e*-folding energies to be directly proportional to Q/A and that the *e*-folding energy of carbon corresponded to $\langle Q_{\mathrm{C}} \rangle = 5.5$, a typical value in gradual events and the solar wind. From ratios of *e*-folding energies, they then derived reasonable mean ionic charges for other species, including $\langle Q_{\mathrm{Fe}} \rangle \sim 10$. This value agrees with measurements at ∼0.26 MeV nucleon^{-1} from *ACE* during this time (Smith et al. 2001).

Except for Fe, the *Wind*/LEMT exponentials account reasonably well for the higher energy data from *ACE*/SIS. The Fe spectra, however, clearly harden with increasing energy. A key to the Fe spectra in Figure 1 may be found in ionic charge states, since Fe—unlike the other species—can arise from a broad charge state distribution. We consider a two-component source,[8] with 95% of the Fe ions coming from solar wind suprathermals and 5% from flare suprathermals. To specify the solar wind component, we used the in-ecliptic, slow solar wind Q_{Fe} distribution from *Ulysses* (von Steiger et al. 2000). This distribution extends from $Q_{\mathrm{Fe}} = 6$ to $Q_{\mathrm{Fe}} = 16$, with mean $\langle Q_{\mathrm{Fe}} \rangle \sim 10$ and rms width ∼2. For flare suprathermals, we used the Q_{Fe} distribution observed by *ACE* in a typical impulsive SEP event (Mewaldt 1999). This distribution has $\langle Q_{\mathrm{Fe}} \rangle \sim 17$ and rms width ∼4. With this 5% flare component, 3% of the

[8] Boberg, Tylka, & Adams (1996) also proposed a two-component Fe source population for SEPs but with a different interpretation on the origin of the high-Q component.

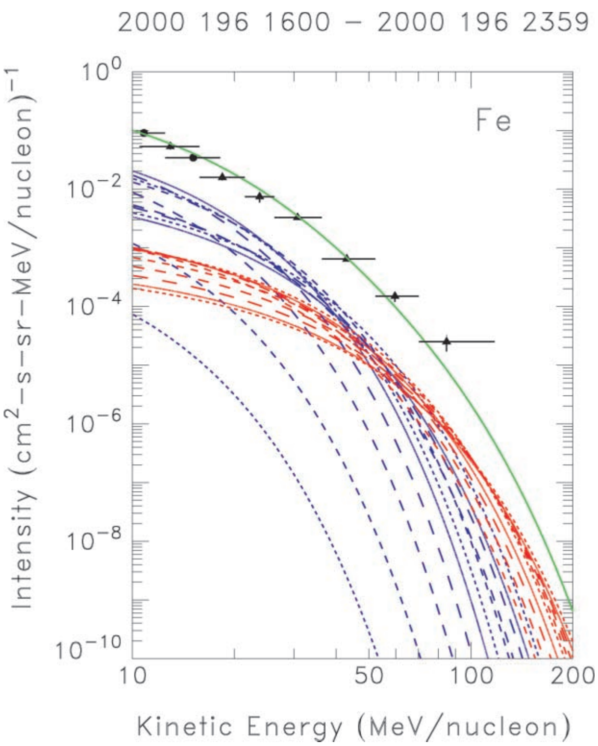

FIG. 2.—Contributions of various ionic charge states to the Fe spectrum. Blue curves are $Q_{Fe} = 6$–16, which arise primarily from the solar wind; red curves are $Q_{Fe} > 16$ from the remnant flare suprathermal component. The green curve is the sum.

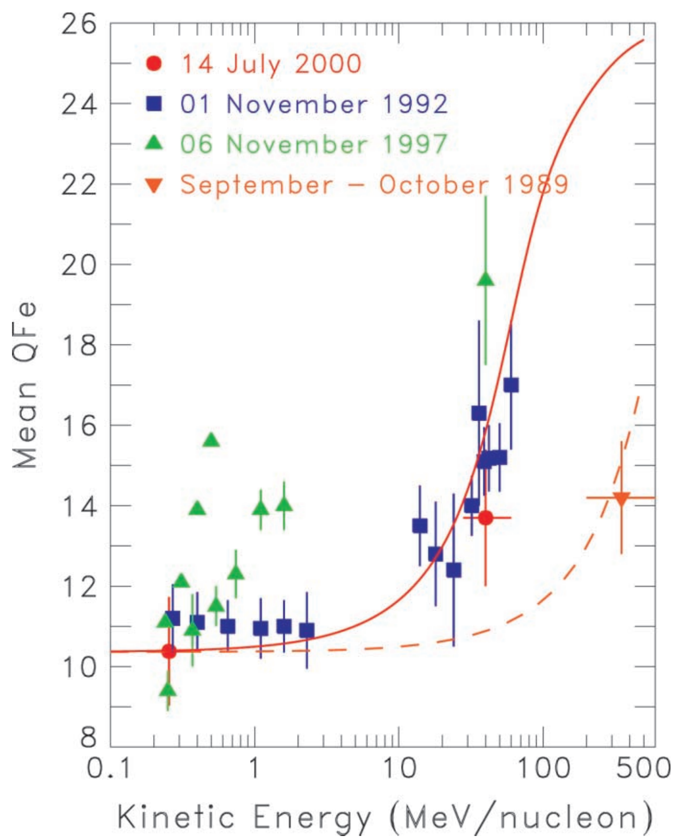

FIG. 3.—Energy dependence of the mean ionic charge state of Fe. The solid curve is evaluated from the spectra in Fig. 2. The dashed curve is calculated with the same source mixture but subjected to a shock with *e*-folding energies an order of magnitude larger. Measurements come from various sources, as noted in the text.

resulting Fe ion source population have $Q_{Fe} > 16$ and less than 0.5% have $Q_{Fe} > 22$. Note that a flare component much larger than 5% is excluded by $\langle Q_{Fe} \rangle \sim 10$ reported by *ACE*.

To model the Fe spectra, we first fitted the spectra below 20 MeV nucleon^{-1}, using the full Ellison & Ramaty (1985) form of $F(E) \sim E^{-\gamma} \exp(-E/E_0)$. We then assumed that the *e*-folding energy (E_0) derived from the less than 20 MeV nucleon^{-1} data corresponds to $Q_{Fe} = 10$. The *e*-folding energies of other Fe ions were then scaled from this value, proportionally to Q_{Fe}. The contribution of each ion was weighted by its fraction in the two-component mixture. Solid curves in Figure 1 show the results of this superposition.

This small admixture of remnant flare suprathermals does remarkably well in accounting for the additional high-energy Fe. Agreement could be further improved by massaging the assumed flare-Q_{Fe} distribution. For example, the slight deficit in the highest energy Fe bins can be removed by increasing the proportion of ions with $Q_{Fe} > 22$. A larger fraction of nearly fully ionized Fe may not be unreasonable: the assumed flare-Q_{Fe} distribution came from a C1.0 X-ray flare, whereas the Bastille Day event was preceded by many, much larger flares.

We similarly modeled other species' energy spectra, using solar wind Q distributions (von Steiger et al. 2000) and assuming the flare component to be fully ionized. However, in that impulsive SEP events are Fe-rich (Reames 1995), the assumed flare component for other species was smaller (∼1.8% for Si and Ne, ∼0.6% for O and C). As shown by the solid curves in Figure 1, these refinements had little impact.

Figure 2 illustrates how various Fe charge states contribute to the overall spectrum. Solar wind charge states dominate at low energies. The remnant flare component becomes more important as energy increases. This modeling implies energy dependence in $\langle Q_{Fe} \rangle$, which is shown by the solid curve in Figure 3. This curve is consistent with the measured $\langle Q_{Fe} \rangle$-values from *ACE* (Smith et al. 2001) and the *Solar, Anomalous, and Magnetospheric Particle Explorer* satellite (Leske et al. 2001) for the Bastille Day event.

For comparison, Figure 3 also shows observed energy-dependent $\langle Q_{Fe} \rangle$ for the 1992 November (Leske et al. 1995; Mason et al. 1995; Oetliker et al. 1997) and 1997 November (Mazur et al. 1999) events. The 1992 event shows energy dependence remarkably similar to that derived here for the Bastille Day event. The 1997 November 6 event, on the other hand, exhibits stronger energy dependence. Since *e*-folding energies in the 1997 November 6 event are large (Torsti et al. 2000), our two-component model cannot account for the rapid rise in $\langle Q_{Fe} \rangle$ below 2 MeV nucleon^{-1}. The 1997 November 6 event has been explained by stripping in the low corona during shock acceleration (Reames et al. 1999; Barghouty & Mewaldt 1999, 2000; Stovpyuk & Ostryakov 2001).

Lest the reader mistakenly infer that high-energy solar Fe must always be nearly fully stripped, the dashed curve in Figure 3 shows another calculation, again using the same source mixture but subjected to a shock with *e*-folding energies an order of magnitude larger. The 1989 September 29 event is an example of such a shock: proton *e*-folding energies exceeded 500 MeV (Lovell, Duldig, & Humble 1998), and Fe ions were observed up to nearly 1 GeV nucleon^{-1} (Tylka & Dietrich

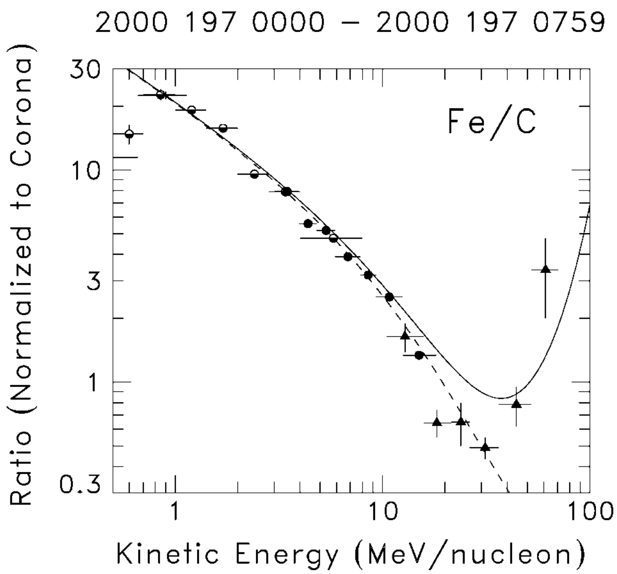

FIG. 4.—Fe/C as a function of energy, normalized to the mean coronal value of 0.288 (Reames 1995). The dashed curve uses solar wind component Fe only, and the solid curve includes solar wind plus remnant flare suprathermals.

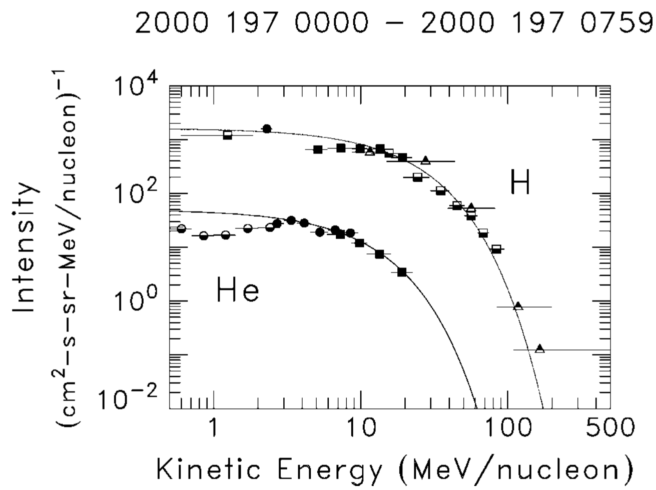

FIG. 5.—H and He spectra in the Bastille Day event, provided by *GOES* (*half-filled triangles*), *Wind*/EPACT/LEMT (*filled circles*), and *IMP8* instruments from NASA/GSFC (*filled squares*) and University of Chicago (*half-filled squares*). *ACE*/EPAM He data (*half-filled circles*) are also shown. Curves are exponentials, normalized to the data and with *e*-folding energies scaled from that of carbon, as described in the text.

1999). In this and other very large events of 1989, Tylka et al. (1995) measured $\langle Q_{\rm Fe} \rangle \sim 14$ at 200–600 MeV nucleon^{-1}.

Finally, Figure 4 shows the Fe/C ratio versus energy. The enhanced Fe/C below ~10 MeV nucleon^{-1} is probably caused by *Q*/*A*-dependent transport, as previously observed in large events (Tylka, Reames, & Ng 1999). The increase in Fe/C above ~30 MeV nucleon^{-1} is due to the remnant flare suprathermal component. Fine-tuning the assumed flare-$Q_{\rm Fe}$ distribution can improve the curve's agreement with the data. The statistical significance of this increase is modest here. However, very similar, complicated energy-dependent Fe/O ratios have been previously reported in large SEP events from a wide range of heliolongitudes (Tylka & Dietrich 1999). Remnant flare suprathermals may also account for the reported association between Fe enhancements above ~40 MeV nucleon^{-1} and ground-level neutron-monitor events (Dietrich & Lopate 1999), which almost always occur during periods of high flare activity.

3. DISCUSSION

One assumption in the foregoing analysis is that the *e*-folding energy is directly proportional to *Q*/*A*. Ellison & Ramaty (1985) argued that this would be the case, provided that the near-shock diffusion coefficient is directly proportional to rigidity. Comparison of H and He (the only ions with precisely known *Q*/*A*) confirmed this behavior in the 1998 April 20 event (Tylka et al. 2000). But in another event, Tylka et al. (2000) discovered a stronger *Q*/*A* dependence.

For a variety of reasons, H and He spectra in the Bastille Day event are of poor quality. Nevertheless, we can examine their consistency with the precise heavy-ion spectra in Figure 1. Figure 5 shows H and He data from *Interplanetary Monitoring Platform 8* (*IMP8*), the *Geostationary Operational Environmental Satellite* (*GOES*), and *Wind*. The solid curves are exponentials, with *e*-folding energy scaled by *Q*/*A* from that of carbon in Figure 1, again assuming $\langle Q_{\rm C} \rangle = 5.5$. These curves nearly match the data, suggesting that *e*-folding energies in the Bastille Day event are indeed nearly proportional to *Q*/*A*.

As we have noted, remnant flare suprathermals in the source population appear to account for several previously unexplained features of large SEP events. The correlation with preceding flare activity also qualitatively explains why some large events (such as 1998 April 20) are Fe-poor at high energies, while others are Fe-rich. Although there are clearly some events (such as 1997 November 6) where conditions at the accelerator are quite different, the hypothesis of remnant flare suprathermals makes it possible to understand a large body of high-energy SEP heavy-ion data in terms of CME-driven shocks, without appeal to other acceleration mechanisms.

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REFERENCES

Barghouty, A. F., & Mewaldt, R. A. 1999, ApJ, 520, L127
———. 2000, in AIP Conf. Proc. 528, Acceleration and Transport of Energetic Particles Observed in the Heliosphere, ed. R. A. Mewaldt, J. R. Jokipii, M. A. Lee, E. Möbius, & T. H. Zurbuchen (New York: AIP), 71
Boberg, P. R., Tylka, A. J., & Adams, J. H., Jr. 1996, ApJ, 471, L65
Desai, M. I., Mason, G. M., Dwyer, J. R., Mazur, J. E., Smith, C. W., & Skoug, R. M. 2001, ApJ, 553, L89
Dietrich, W. F., & Lopate, C. 1999, Proc. 26th Int. Cosmic-Ray Conf. (Salt Lake City), 6, 71
Ellison, D., & Ramaty, R. 1985, ApJ, 298, 400
Fisk, L. A., Gloeckler, G., Zurbuchen, T. H., & Schwadron, N. A. 2000, in AIP Conf. Proc. 528, Acceleration and Transport of Energetic Particles Observed in the Heliosphere, ed. R. A. Mewaldt, J. R. Jokipii, M. A. Lee, E. Möbius, & T. H. Zurbuchen (New York: AIP), 229
Gloeckler, G., et al. 1999, Geophys. Res. Lett., 26, 157
Gold, R. E., et al. 1998, Space Sci. Rev., 86, 541
Leske, R. A., Cummings, J. R., Mewaldt, R. A., Stone, E. C., & von Rosenvinge, T. T. 1995, ApJ, 452, L149

Leske, R. A., Mewaldt, R. A., Cummings, A. C., Stone, E. C., & von Rosenvinge, T. T. 2001, in Proc. Joint *SOHO*/*ACE* Workshop: Solar and Galactic Composition, ed. R. F. Wimmer-Schweingruber (New York: AIP), in press
Lovell, J. L., Duldig, M. L., & Humble, J. E. 1998, J. Geophys. Res., 103, 23,733
Mason, G. M., Mazur, J. E., & Dwyer, J. R. 1999, ApJ, 525, L133
Mason, G. M., Mazur, J. E., Looper, M. D., & Mewaldt, R. A. 1995, ApJ, 452, 901
Mazur, J. E., Mason, G. M., Looper, M. D., Leske, R. A., & Mewaldt, R. A. 1999, Geophys. Res. Lett., 26, 173
Mewaldt, R. A. 1999, in AIP Conf. Proc. 516, 26th Int. Cosmic-Ray Conf.: Invited, Rapporteur, and Highlight Papers, ed. B. L. Dingus, D. B. Kieda, & M. H. Salamon (New York: AIP), 265
Oetliker, M., et al. 1997, ApJ, 477, 495
Reames, D. V. 1995, Adv. Space Res., 15(7), 41
Reames, D. V., Ng, C. K., & Tylka, A. J. 1999, Geophys. Res. Lett., 26, 3585
———. 2001, ApJ, 548, L233
Smith, C. W., et al. 2001, Sol. Phys., in press
Stone, E. C., et al. 1998, Space Sci. Rev., 86, 357
Stovpyuk, M. F., & Ostryakov, V. M. 2001, Sol. Phys., 198, 163
Torsti, J., Mäkelä, P., Teittinen, M., & Laivola, J. 2000, ApJ, 544, 1169
Tylka, A. J., Boberg, P. R., Adams, J. H., Jr., Beahm, L. P., Dietrich, W. F., & Kleis, T. 1995, ApJ, 444, L109
Tylka, A. J., Boberg, P. R., McGuire, R. E., Ng, C. K., & Reames, D. V. 2000, in AIP Conf. Proc. 528, Acceleration and Transport of Energetic Particles Observed in the Heliosphere, ed. R. A. Mewaldt, J. R. Jokipii, M. A. Lee, E. Möbius, & T. H. Zurbuchen (New York: AIP), 147
Tylka, A. J., & Dietrich, W. F. 1999, Radiat. Meas., 30(3), 345
Tylka, A. J., Reames, D. V., & Ng, C. K. 1999, Geophys. Res. Lett., 26, 2141
Tylka, A. J., et al. 2001, Proc. 27th Int. Cosmic-Ray Conf. (Hamburg), in press
von Rosenvinge, T. T., et al. 1995, Space Sci. Rev., 71, 155
von Steiger, R., et al. 2000, J. Geophys. Res., 105, 27,217
Zurbuchen, T. H., Fisk, L. A., Schwadron, N. A., & Gloeckler, G. 2000, in AIP Conf. Proc. 528, Acceleration and Transport of Energetic Particles Observed in the Heliosphere, ed. R. A. Mewaldt, J. R. Jokipii, M. A. Lee, E. Möbius, & T. H. Zurbuchen (New York: AIP), 215