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FLARE- AND SHOCK-ACCELERATED ENERGETIC PARTICLES IN THE SOLAR EVENTS OF 2001 APRIL 14 AND 15

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ABSTRACT

We report heavy-ion composition and spectra for the solar energetic particle (SEP) events of 2001 April 14 and 15, using the combined capabilities of the *Advanced Composition Explorer* (*ACE*), *Wind*, and the *Interplanetary Monitoring Platform 8* (*IMP-8*) to cover the energy range from ∼30 keV nucleon^{-1} to ∼400 MeV nucleon^{-1}. These two events are, respectively, the largest impulsive event and the largest ground-level event observed so far in solar cycle 23. These events arose from the same active region and launched into similar interplanetary conditions. Both were associated with large western flares and fast coronal mass ejections (CMEs). However, the two events are distinctly different, thereby providing useful reminders of the fundamental differences between flare- and shock-accelerated SEPs. The detailed observations present challenges for our theoretical understanding of SEP production. Of particular note is the fact that iron has a harder power-law energy spectrum than oxygen above ∼3 MeV nucleon^{-1} in the shock-dominated April 15 event. This spectral difference, which is seen in many other gradual events of various sizes and heliolongitudes, leads to enhanced Fe/O at high energies. Simple shock acceleration models predict the same power-law index for all species. Thus, understanding the origin of this spectral difference will significantly contribute to the resolution of the ongoing debate about the relative roles of CME-driven shocks and flares in producing high-energy solar heavy ions.

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

1. INTRODUCTION

2001 April produced one of the most remarkable sequences of solar activity in solar cycle 23. A single active region[9] (NOAA Active Region 9415) spawned ∼20 C-, M-, and X-class X-ray flares, a number of coronal mass ejections (CMEs), and several major solar energetic particle (SEP) events (Reames & Tylka 2002; Lockwood et al. 2002). In this Letter, we focus on two events: the 2001 April 14 event, which was associated with an M1.0 X-ray flare at S16°W71° and an 830 km s^{-1} CME, and the 2001 April 15 event, for which the associated X-ray flare was larger (X14.4 at S20°W85°) and the CME faster (1200 km s^{-1}). Interplanetary plasma conditions during these events, at least as measured near 1 AU, were relatively quiet, apart from a gradual decline in the solar wind speed from ∼650 km s^{-1} on April 14 to ∼400 km s^{-1} on April 17. Metric[10] and interplanetary[11] type II radio emission, which are generally interpreted as evidence of shock acceleration, were also reported for the 2001 April 15 event. No type II emissions have been reported for the 2001 April 14 event.

2. OBSERVATIONS

Figure 1 shows hourly time-intensity profiles. The larger event on 2001 April 15 is clearly evident. The small 2001 April 14 event occurs in the decay phase from an earlier large event. It is barely discernible as an increase of ∼10^{-2} protons cm^{-2} s sr MeV at ∼20 MeV but clearly stands out at lower energies and in the heavy-ion channels.

A close examination of Figure 1 reveals interesting compositional differences between the two events. Before the events, the Fe/O ratio was near coronal levels (∼0.1; Reames 1995) at all energies in Figure 1. In the April 14 event, the Fe and O time lines lie nearly on top of each other at all three energies. This indicates not only an ∼10-fold enhancement in Fe/O over coronal abundances but also that the Fe/O ratio is roughly independent of both time and energy. Given that SEP transport generally affects species in a rigidity-dependent way, this behavior suggests that Fe and O have nearly identical, energy-independent mass-to-charge (A/Q) ratios in the April 14 event. In the April 15 event, on the other hand, Fe and O intensities are comparable only at *ACE*/ULEIS energies. At the higher *Wind*/LEMT and *ACE*/SIS energies, the Fe and O profiles overlap only during the first few hours. Thereafter, the Fe and O traces separate, giving roughly twice coronal Fe/O at ∼3 MeV nucleon^{-1} and a somewhat larger value at ∼10 MeV nucleon^{-1}.

Figure 2 examines more closely the elemental composition of these events, using the event-integrated ratios at ∼3–10 MeV nucleon^{-1} from *Wind*/LEMT. To within a factor of 2 or so, the

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[9] Information on flares and active regions was taken from http://www.ngdc.noaa.gov/stp/SOLAR/sgdintro.html. CME parameters were provided by http://cdaw.gsfc.nasa.gov/CME_list. Shock information was supplied by D. Berdichevsky 2002, private communication.

[10] From the Potsdam-Tremsdorf Solar Radio Observatory (http://www.aip.de/groups/osra/index_typeII.html).

[11] From the *Wind*/Waves experiment (http://lep694.gsfc.nasa.gov/waves/waves.html).

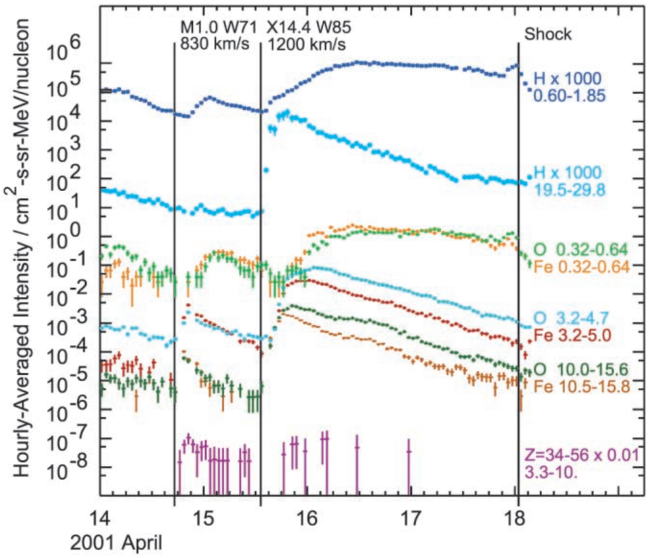

FIG. 1.—Hourly averaged time-intensity profiles for various species and energies (in units of MeV nucleon^{-1}), as noted in the figure. Protons (multiplied by 1000) come from the University of Chicago's Cosmic-Ray Nuclei Experiment (CRNE; Garcia-Munoz, Mason, & Simpson 1975) on the *Interplanetary Platform 8* (*IMP-8*). Fe and O at 0.32–0.64, ~3–5, and ~10–15 MeV nucleon^{-1} come, respectively, from the Ultra Low Energy Isotope Spectrometer (ULEIS; Mason et al. 1998) on the *Advanced Composition Explorer* (*ACE*), the Low Energy Matrix Telescope (LEMT) in the Energetic Particle Acceleration, Composition, and Transport (EPACT) experiment (von Rosenvinge et al. 1995) on *Wind*, and the Solar Isotope Spectrometer (SIS; Stone et al. 1998) on *ACE*. Also shown are measurements (multiplied by 0.01) of ions with atomic numbers Z = 34–56 at ~3.3–10 MeV nucleon^{-1} from *Wind*/LEMT. The vertical lines mark the associated flares, CMEs, and shocks.

composition in the April 15 event is consistent with coronal abundances all the way from He (atomic number $Z = 2$) to Sn-Ba ($Z = 50$–56), at least at these energies. This is also true of two other large events from the same active region that occurred just before and after the events under consideration here. The April 14 event, however, shows strong enhancements at Ne, S, Ca, Fe, and most dramatically, in the trans-Fe elements, where abundances are ~100–1000 larger than nominal coronal values. These very large abundance enhancements are generally not expected from shock acceleration, which energizes particles from the source plasma in a more-or-less unbiased fashion. However, similar trans-Fe enhancements have been reported previously in flare-accelerated SEP events (Reames 2000).

ACE/ULEIS observed ^{3}He/^{4}He = 6.5% ± 1.2% at 0.5–2.0 MeV nucleon^{-1} in the April 14 event, a roughly hundred-fold enhancement over the average solar-wind value of 0.041% ± 0.003% (Gloeckler et al. 1999). By contrast, in the April 15 event, ^{3}He/^{4}He = 0.22% ± 0.05%, only ~5 times the solar-wind average. Similar values have been observed in many other large gradual solar particle events (Mason et al. 2002) and have been attributed to remnant flare suprathermals in the source material (Mason, Mazur, & Dwyer 1999).[12]

3. ENERGY SPECTRA AND COMPOSITION

The foregoing discussion implicates distinctly different acceleration mechanisms in these two events, at least at ~1–10 MeV nucleon^{-1} . We now examine their characteristics over a larger energy range. Figure 3 shows event-integrated Fe and O spectra in the April 14 event,[13] extending from ~30 keV nucleon^{-1} to ~30 MeV nucleon^{-1}, where the oxygen intensity falls to background levels. The spectra are not power laws but curve continuously, a well-known signature of stochastically accelerated ions (Forman, Ramaty, & Zweibel 1986). The Fe and O spectra are also very similar, a feature of many flare-accelerated SEP events (Mason et al. 2002). The top panel of Figure 4 shows the apparent energy independence of Fe/O in this event. The average Fe/O value is strongly enhanced at 10.5 ± 0.2 times coronal.

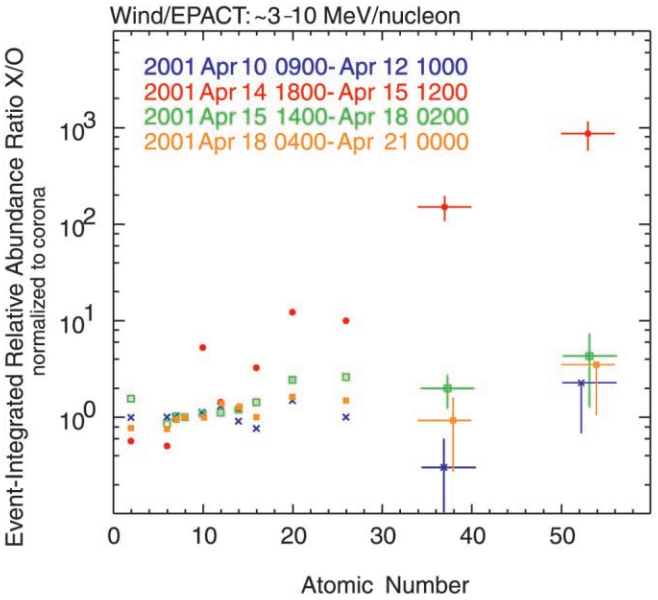

FIG. 2.—Event-integrated elemental ratios (normalized to oxygen and to nominal coronal values [Reames 1995, 2000]) vs. atomic number for four events in 2001 April (distinguished by color) at ~3.3–10 MeV nucleon^{-1} from *Wind*/LEMT. Upper limits (corresponding to one ion) are shown for Z = 50–56 in the April 10 (*blue*) and April 18 (*gold*) events.

Figure 5 shows O and Fe spectra in the April 15 event, along with power-law fits to measurements above 3 MeV nucleon^{-1}. Some discrepancies among the instruments are apparent. Nevertheless, Fe clearly has a significantly harder power-law index (γ = 2.41 ± 0.02) than oxygen[14] (γ = 2.77 ± 0.02). Similar spectral differences between Fe and O have been reported previously in large, ground-level SEP events (Tylka & Dietrich 1999). For Fe, the fitted power law roughly describes the data down to ~0.4 MeV nucleon^{-1}. At even lower energies, both spectra flatten. This flattening has been ascribed to transport through proton-amplified Alfvén waves (Ng, Reames, & Tylka 1999; Reames 1999; Tylka 2001).

The spectral differences in Figure 5 lead to strongly energy-dependent Fe/O in the April 15 event, as shown in the bottom panel of Figure 4. Although there are some unresolved

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[12] For the other events in Fig. 2, *ACE*/ULEIS gives ^{3}He/^{4}He = 0.25% ± 0.06% in the April 18 event, and an upper limit, <0.16% (90% confidence level), in the April 10 event.

[13] There are large anisotropies in this event. Whereas *Wind* and *IMP-8* average over the whole ecliptic plane, *ACE* primarily looks toward the Sun, giving higher acceptance-averaged intensities in this case. To compensate for this effect in Fig. 3, the LEMT Fe and O have been multiplied by a factor of 2 (as determined by comparing LEMT and SIS O at ~10 MeV nucleon^{-1}). This change does not affect the Fe/O ratio. No such correction was needed in the April 15 event, in which anisotropies are small.

[14] The fitted power-law indices for C, N, Ne, Mg, Si, and S are the same as that of oxygen to within uncertainties. The Ca spectrum is significantly harder, and its fitted power-law index is the same as that of Fe to within uncertainties.

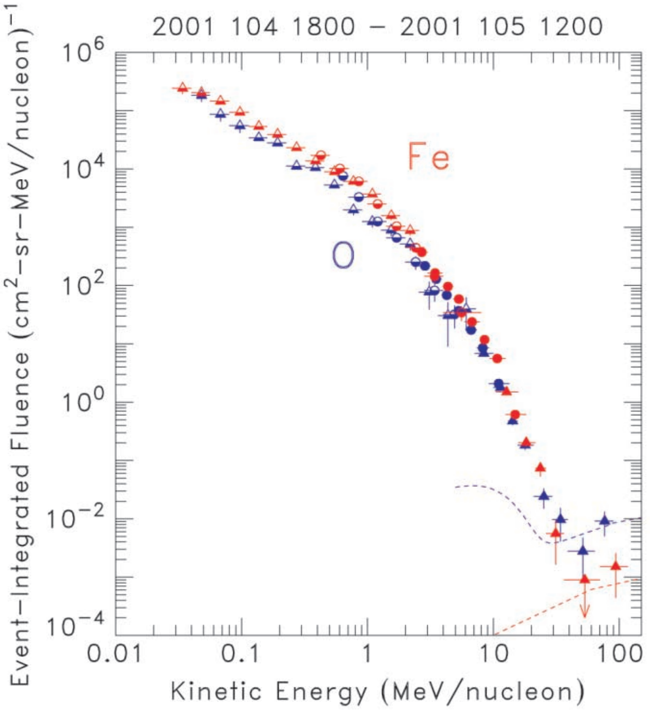

FIG. 3.—Event-integrated Fe (*red*) and O (*blue*) fluences in the 2001 April 14 event from *ACE*/ULEIS (*half-filled triangles*), *ACE*/Electron, Proton, and Alpha Monitor (EPAM; Gold et al. 1998; *half-filled circles*), *Wind*/LEMT (*filled circles*), and *ACE*/SIS (*filled triangles*). The dashed lines show estimated Galactic and anomalous cosmic-ray backgrounds. The time interval for the event integration was as noted, except that a sliding time window, consistent with velocity dispersion, was used below ∼0.5 MeV nucleon^{-1} (Mason, Dwyer, & Mazur 2000).

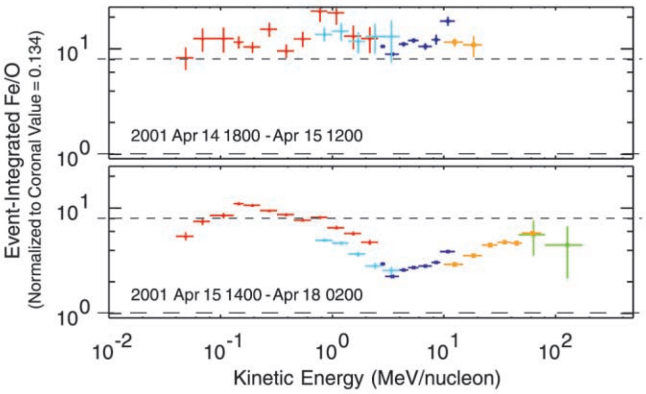

FIG. 4.—Event-integrated Fe/O (normalized to the coronal value, 0.134 [Reames 1995]) vs. energy for the 2001 April 14 (*top*) and April 15 (*bottom*) events. Data come from *ACE*/ULEIS (*red*), *ACE*/EPAM (*light blue*), *Wind*/LEMT (*dark blue*), *ACE*/SIS (*gold*), and *IMP-8*/CRNE (*green*). The short- and long-dashed reference lines mark the average values (Reames 1995) for ^{3}He-rich and gradual SEP events, respectively.

discrepancies among instruments, the pattern is clear. Above ∼3 MeV nucleon^{-1}, Fe/O increases roughly as a power law, consistent with the spectra in Figure 5. At ∼3 MeV nucleon^{-1}, Fe/O goes through a minimum. Below ∼1 MeV nucleon^{-1}, Fe/O exceeds the average value in ^{3}He-rich impulsive events. However, unlike in the April 14 event, this enhancement has nothing to do with a flare contribution: ionic charge state measurements at ∼0.25–1.0 MeV nucleon^{-1} from the *Solar, Anomalous, and Magnetospheric Particle Explorer* (*SAMPEX*) give $\langle Q\mathrm{Fe}\rangle = 11.7 \pm 0.3$ (Mazur & Mason 2001), consistent with measurements in other large SEP events and far below $\langle Q\mathrm{Fe}\rangle \sim 18$–20 that is characteristic of flare-accelerated ions at these energies (Luhn et al. 1987; Möbius et al. 1999). The Fe/O enhancement below ∼1 MeV nucleon^{-1} in this event is therefore presumably a transport-induced distortion, arising because of iron's higher A/Q and larger scattering mean free path. Below ∼0.15 MeV nucleon^{-1}, the event-averaged intensity is dominated by the associated energetic storm particle event late on April 17 (see Fig. 1), and Fe/O is somewhat smaller.

The spectral difference between Fe and O in the April 15 event causes Fe/O at ∼50 MeV nucleon^{-1} to approach the average value for impulsive ^{3}He-rich events (Reames 1995). The increase in Fe/O with energy above ∼3 MeV nucleon^{-1} is not an artifact of event integration. Figure 6 shows Fe/O versus time at various energies. Except for the first 4 hr of the event, when the velocity dispersion and the rigidity-dependent rates of rise are relevant, the ordering of Fe/O by energy is generally clear throughout the event. At all energies, Fe/O drops from an initially enhanced value, qualitatively consistent with particle transport when Fe scatters less than O. However, on the last day of the event, the spectral difference between Fe and O is exacerbated, causing Fe/O to strongly increase at the highest energies. Intensities above ∼1 MeV nucleon^{-1} show no increases related to the shock's arrival at 1 AU (see Fig. 1), and the observed intensities are only a few percent of earlier levels. The late-phase behavior in Figure 6 is not due to background (since the observed Fe intensities are still >100 times

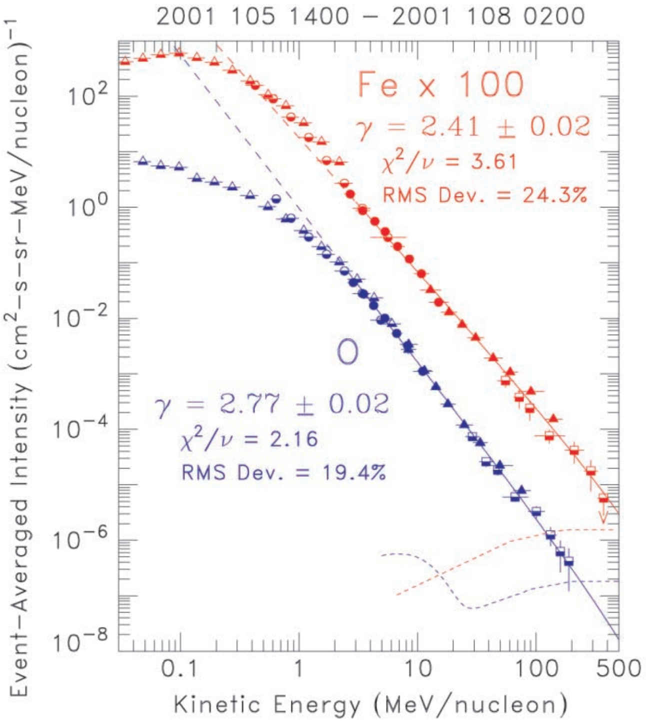

FIG. 5.—Event-averaged O (*blue*) and Fe (*red*, multiplied by 100) spectra in the 2001 April 15 event. Data sources are as in Fig. 3, but with additional measurements from the *IMP-8*/CRNE (*half-filled squares*). The short-dashed curves show the contemporaneous anomalous and Galactic cosmic-ray backgrounds, also color-coded and multiplied by 100 for Fe. Power-law fits to data points above 3 MeV nucleon^{-1} are shown. The reduced χ^2 of the fits and rms deviations of fitted data points from the fit are also noted. The fit quality is acceptable, given that we are combining independent data from five instruments on three satellites.

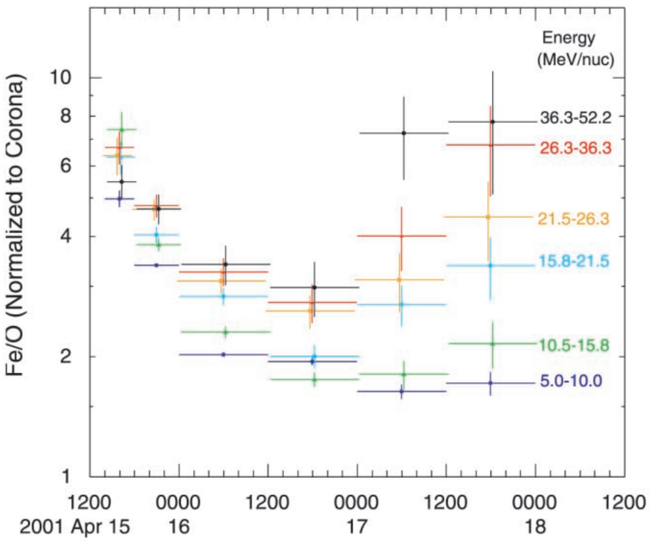

FIG. 6.—Fe/O (normalized to the coronal value, 0.134 [Reames 1995]) vs. time in the 2001 April 15 event, at various energies, as given in the figure.

Galactic levels) nor is it due to the onset of another event. The behavior reflects a flatter decay-phase time profile for Fe, perhaps caused by its longer scattering mean free path in a magnetic bottle (Reames & Ng 2002).

4. DISCUSSION

Very strong heavy-ion enhancements, as observed in the April 14 event, are generally believed to be the product of stochastic acceleration at flares.[15] The leading theory for this mechanism (Miller 2000) invokes cascading Alfvén waves that sequentially energize ions, starting at those with the highest A/Q ratios. The 2001 April 14 observations may pose new challenges for this theory. In particular, it has not been demonstrated that this theory can actually produce the very large trans-Fe enhancements seen here and in other impulsive events (Reames 2000). Moreover, in order to obtain the observed enhancements (at least through Fe), the source plasma must have a temperature of 3–5 MK (Reames, Meyer, & von Rosenvinge 1994), where oxygen would be fully stripped, but the mean A/Q of Fe would be ∼4. (Additional stripping during or after acceleration [Miller & Viñas 1993] would then account for the higher ionic charge states that are actually observed.) Since Fe and O start with dissimilar A/Q values, the theory generally predicts different spectral shapes for Fe and O (see Fig. 16 of Mason et al. 2002). Thus, the similarity of the Fe and O spectra in Figure 3 may also be problematic for the theory.

The explanation of the April 15 event in terms of shock acceleration also presents new challenges. First, shock-accelerated spectra are generally expected to be power laws multiplied by exponential rollovers (Ellison & Ramaty 1985). In many events, these exponential rollovers are clearly seen (e.g., Tylka et al. 2000, 2001). In the April 15 event, such rollovers also presumably occur, but at energies beyond where we are able to measure. Shock theory must provide an explanation for this variability. Second, the spectral difference between Fe and O in Figure 5 presumably reflects the fact that Fe ions arise from a broader distribution of A/Q values, including values not attainable by other species. But it is not clear how this spectral difference comes about since simple shock theory predicts that the power-law index should be the same for all species, independent of A/Q.

Eichler (1979) noted that a "smoothed shock," with finite width, could yield harder power laws for higher A/Q species: higher A/Q species would have larger scattering mean free paths that would enable them to traverse larger distances across the shock and thereby sample a larger compression ratio. A smoothed shock has been reported only once near 1 AU (Terasawa et al. 1999); perhaps such shocks are more common near the Sun. However, it is not clear how the smoothed-shock scenario can account for the increase in the Fe charge state with energy observed by *SAMPEX* for this event (Mazur & Mason 2001; Labrador et al. 2002). Figure 6 may hint that transport processes also contribute to spectral differences between Fe and lighter ions.

One might consider that both flare- and shock-acceleration mechanisms operate in the April 15 event, with the flare becoming more important at high energies. But there is no evidence of two acceleration mechanisms in either time profiles or energy spectra. In particular, the spectra in Figure 5 are described by a single power law above ∼3 MeV nucleon^{-1}, without any inflection point indicative of more than one acceleration mechanism.

Finally, we note that not all large shock-accelerated SEP events show the complicated energy-dependent Fe/O seen in the April 15 event. The largest events in cycle 23 tend to have highly suppressed Fe/O at high energies (e.g., Tylka et al. 2000) or nearly nominal values (e.g., Tylka et al. 2001). But the 2001 April 15 event is also not unique: at least a quarter of the large events of cycle 23 show similar spectral characteristics (A. J. Tylka et al. 2002, in preparation). This behavior appears in events from a wide range of heliolongitudes and for gradual events of all sizes, not just ground-level events. Thus, the questions raised here will be important for our overall understanding of processes that produce SEPs.

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[15] The 2001 April 14 event is an example of an impulsive SEP event accompanied by both a flare and a CME. Kahler, Reames, & Sheeley (2001) discussed similar events and found that the associated CMEs tended to be relatively narrow, with widths ∼10°–40°. That is not the case here, where the CME is ∼110° wide. This particular CME was apparently not fast enough to drive a shock, at least not along the Sun-Earth magnetic field line.

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