HTML ABSTRACT + LINKS

Solar Energetic Particle Spectral Breaks

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Abstract. The five large solar particle events during October-November 2003 presented an opportunity to test shock acceleration models with in-situ observations. We use solar particle spectra of H to Fe ions, measured by instruments on ACE, SAMPEX, and GOES-11, to investigate the Q/M-dependence of spectral breaks in the 28 October 2003 event. We find that the break energies scale as $(Q/M)^b$ with $b \approx 1.56$ to 1.75, somewhat less than predicted. We also conclude that SEP spectra >100 MeV/nucleon are best fit by a double power-law shape.

INTRODUCTION

The Halloween 2003 period provided the opportunity to study the spectra of five large solar energetic particle (SEP) events within a 10-day period, each associated with an X-class flare and very fast (>1500 km/sec) CME. An overview of this period is shown in Figure 1, which includes oxygen intensities in several energy intervals. In the two largest events (events 2 and 3), particles were still being accelerated to ~10 MeV/nuc when the shock reached 1 AU. Two studies of these five events [1, 2] have shown that elements from H to Fe have rather prominent spectral breaks in the energy range from ~3 to ~30 MeV/nuc, similar to those in earlier studies by Tylka et al. [3, 4]. Li, Zank and Rice [5; hereinafter LZR] have recently extended the model of Zank, Rice and Wu [6] to heavier ions. In their model the break energy is proportional to the square of the charge-to-mass ratio (Q/M), where Q is the charge state and M is the ion's mass number. In this paper we combine measurements from instruments on ACE, SAMPEX and GOES-11 to obtain SEP energy spectra for the five Halloween events and the Jan. 20, 2005 event. We test the Q/M dependence predicted by LZR with observations of spectral breaks for nine elements following the strong shock from the Oct 28, 2003 SEP event. We also show that a double power-law shape provides excellent fits to the high-energy (>100 MeV/nuc) spectra in these events.

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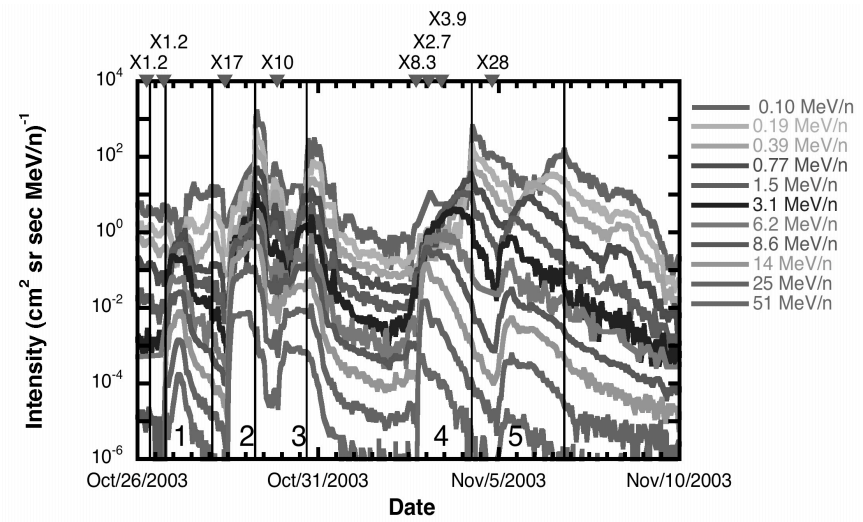

Figure 1: Time history of energetic oxygen nuclei measured by the SIS and ULEIS instruments on ACE (from Cohen et al. [1]). Five large SEP events are evident (numbered 1 to 5). Interplanetary shocks are indicated by vertical solid lines and X-class flares are shown along the top.

OBSERVATIONS

The shock from the 28 October 2003 event reached Earth within 19 hours followed by driver gas traveling at ~2000 km/sec [7]. Upon arrival at 1 AU this shock was still accelerating oxygen to ~10 MeV/nuc (see Figure 1) and protons to ~30 MeV [2]. Figure 2 shows energy spectra measured during the 6 hours following the arrival of the shock. Note that all species show a relatively sharp break at energies ranging from a few MeV/nuc to ~30 MeV/nuc. The location of the breaks depends on species – lighter species have higher break energies than heavier species like Fe (see also Tylka et al. [3]). These spectra provide an excellent opportunity to test the prediction of LZR [5] that the location of the breaks should scale as $(Q/M)^2$.

The spectra in the left panel of Figure 2 were fit by a two-step procedure. In the first step the points above and below the apparent break were individually fit with power-laws, giving average power-law indices of –1.43 below the break and –4.1 above the break. In the second step power-laws with these fixed, average slopes were individually scaled to fit the points above and below the break, and the intersection of the two power-laws was defined as the break energy. The break energies ranged from 31 MeV for protons to 4.1 MeV/nuc for Fe.

Ellison and Ramaty [8] proposed that shock-accelerated SEPs would have spectra of the form:

$$dJ/dE = KE^{-\gamma} \exp(-E/E_o). \quad (1)$$

Here J is the intensity, K, E_o, and γ are constants, and we have treated E as energy/nuc. This spectrum, which is a power-law at low energies with an exponential roll-over at

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high energies, has been used extensively by Tylka et al. [3, 4] to fit SEP spectra, and we use this form to obtain a second estimate of the break energy. The average value of γ was 1.3. Using $\gamma = 1.3$ the spectra were then refit to determine E_o for each species, which ranged from 31 MeV for protons to 3.5 MeV/nuc for Fe (see Figure 3).

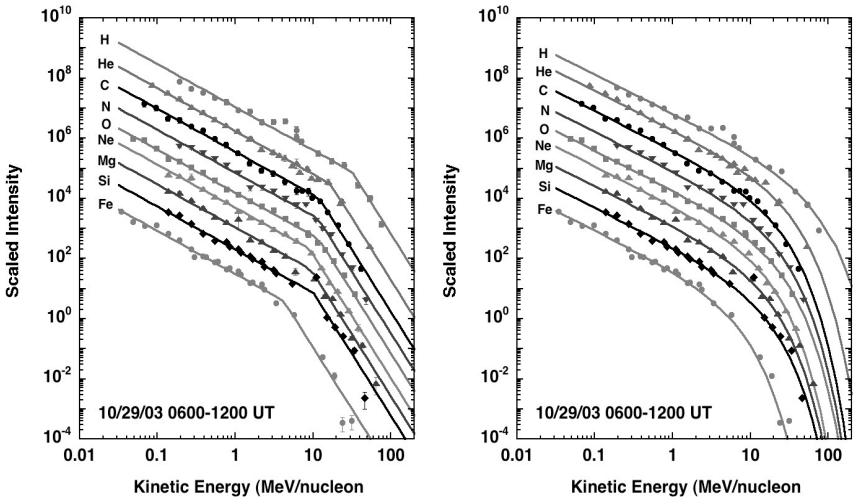

FIGURE 2. (Left) Spectra from the period following the shock on 29 October are fit with two power-laws using a fixed slope of –1.43 at low energy and –4.1 at high energy. The intersection of these fits determines the break energy. (Right) The same data are fit with the Ellison-Ramaty spectral form using a fixed value of –1.3 for the power-law index. Data are from the SIS, ULEIS and EPAM instruments on ACE, and the EPS sensor on GOES-11 (see Mewaldt et al. [2] for additional details). Each element has been multiplied by a scale factor to separate the spectra.

In order to investigate the Q/M-dependence of the breaks we use charge-state measurements from the same event by Labrador et al. [9] obtained using the geomagnetic method with the MAST instrument on SAMPEX [10]. The energy intervals range from 15 to 60 MeV/nuc for O to 27 to 90 MeV/nuc for Fe. The two estimates of the break energies are plotted against Q/M in Figure 3.

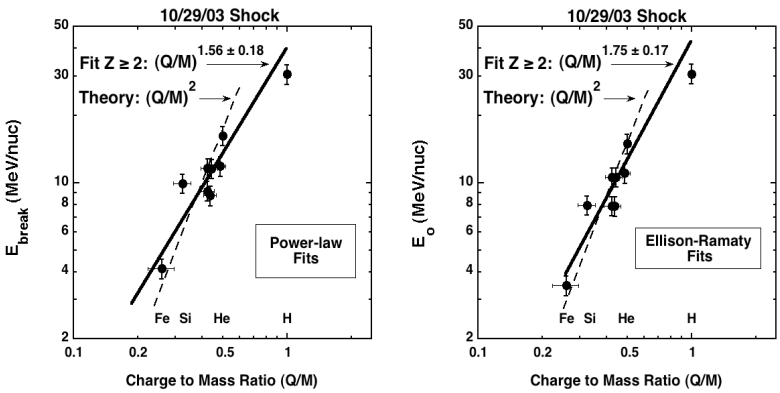

FIGURE 3. Break energies from Figure 2 are plotted versus Q/M. Fits to the Z≥2 data give somewhat weaker dependence on Q/M than is expected from the theory of LZR [6].

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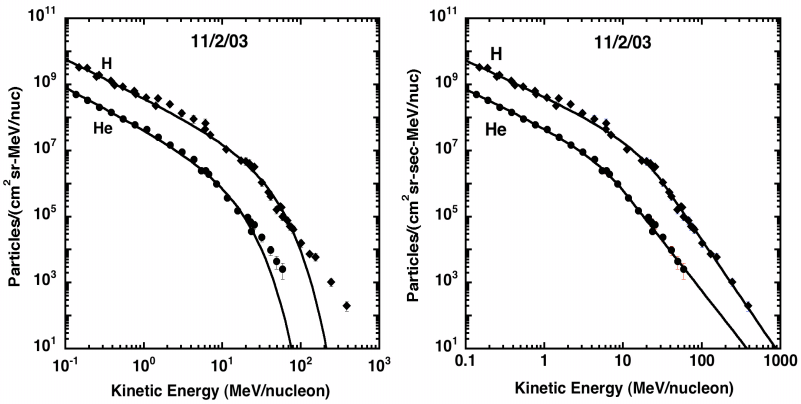

FIGURE 4. H and He Fluence spectra for the Nov. 2, 2003 event are better fit with the double power-law form of Band et al. [11; Right] than with the Ellison-Ramaty spectral form (Left).

The fluence spectra for the five Halloween events (integrated over the events) also have spectral breaks [2, 1]. For these spectra the Ellison-Ramaty form is adequate up to ~100 MeV/nuc, but fails to fit the spectra at higher energies [2]. Figure 4 illustrates that spectra >100 MeV/nuc are better fit by a double power-law formula from Band et al. [11], given by:

$$dJ/dE = CE^{-\gamma_a} \exp(-E/E_o) \text{ for } E \leq (\gamma_b - \gamma_a)E_o;$$

$$dJ/dE = CE^{-\gamma_b}\{[(\gamma_b - \gamma_a)E_o]^{(\gamma_b-\gamma_a)} \exp(\gamma_a - \gamma_b)\} \text{ for } E \geq (\gamma_b - \gamma_a)E_o. \qquad (2)$$

Here γ_a is the low-energy power-law slope and γ_b is the high-energy power-law slope. Spectra from the five Halloween events are shown in Figure 5, along with the Jan. 20, 2005 event, where the breaks are at lower energy, and the spectra above the breaks are much harder. In this event the H and He spectra above the breaks extend as power-laws with an index ≈ -2.2 for about two decades in energy or more.

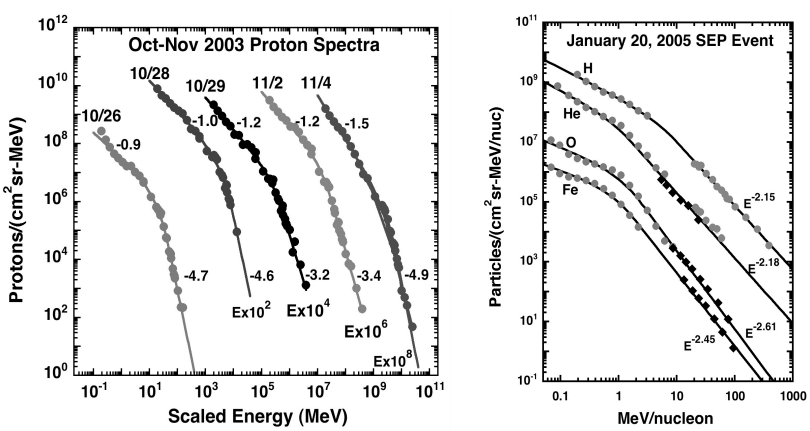

FIGURE 5. (Left) Fluence spectra for the Oct.-Nov. 2003 events fit with the Band et al. shape [11]. Spectral indices above and below the break are indicated. (Right) The 20 Jan. 2005 event had a double power-law shape with a very hard spectrum. Data are from ACE, SAMPEX and GOES-11 [2].

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DISCUSSION

In the model of LZR [5] streaming protons escaping upstream from the shock generate enhanced turbulence in the form of Alfven waves that extends over ~2 decades in wave number (k; see Lee [12] and Ng, Reames, and Tylka [13], hereinafter NRT]). The proton-amplified Alfven waves play a key role in scattering particles and keeping them near the shock where they can be efficiently accelerated. According to LZR, the break in the power-law spectrum for a given species occurs at the maximum achievable momentum/nuc (p_{max}) for which there is efficient acceleration, which corresponds to the momentum/nuc that resonates with the minimum k-value (k_{min}) for which there is enhanced turbulence. Thus, for species i,

$$k_{min} = (Q_i/M_i)(eB/c\, p_{max}), \tag{3}$$

where B is the magnetic field strength, e the electron charge, and c the speed of light. Converting from momentum/nuc to energy/nuc (E) the break-energy of species i ($E_{max,i}$) is related to that of protons by

$$E_{max,i} = (Q_i/M_i)^2 E_{max,p}\ . \tag{4}$$

In the LZR model the sudden decrease in the turbulence level at k values below k_{min} leads to a sudden increase in the diffusion coefficient, thus allowing higher-energy particles to freely escape upstream from the shock. There are similar, though less sharp, breaks in the wave spectra calculated by NRT. Recently, evidence has been reported for proton-amplified Alfven waves at 1 AU in large SEP events [14, 15].

The location of the breaks for He to Fe (Figure 3) are reasonably consistent with the power-law behavior predicted by LZR, although the slope that we find (1.56 to 1.75) is somewhat less than predicted. Note that the proton break energy is low compared with the fits to the heavy ions. Li and Zank (personal communication) have pointed out that while heavy ions should act like test particles, protons may not, because protons produce the waves that govern this process [5, 13].

Cohen et al. [1] analyzed the location of spectral breaks for $8 \leq Z \leq 26$ ions in the fluence spectra of the five Halloween events. Using average SEP charge states measured at lower energy they find that the breaks scale like $(Q/M)^b$ with b = 0.9 to 1.5. Mewaldt et al. [2] found that breaks in the H and He fluence spectra suggest b = 0.7 to 1.3, similar to Tylka et al. [3]. It is possible that the expected Q/M dependence in fluence spectra is washed out somewhat because the maximum energy (E_{max}) is greater closer to the Sun than at 1 AU. Fluence spectra from 1 AU inevitably include particles accelerated close to the Sun as well as those accelerated locally [5].

There are also likely to be longitudinal differences in the break energies that may depend on shock geometry [4]. In fluence spectra the magnetic connection point to the shock evolves with time, and this evolution depends on the event location. These considerations, not accounted for in most theoretical models, complicate comparisons such as these. Presumably, contributions from particles accelerated closer to the Sun or at different longitudes are minimized in the Oct. 29, 2003 shock period, where local acceleration dominates, and the Q/M-behavior comes closest to the model predictions.

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Cohen et al. [1] suggested thatthe location of spectral breaks in fluence spectra is governed by diffusion processes, such as escape upstream from the shock. In this case, spectral breaks for different species should occur at the same value of the diffusion coefficient [16]. Cohen et al. [1] found that the fluence spectra of $8 \leq Z \leq 26$ ions in the Halloween events shared a common spectral shape (see also [2]). Assuming a diffusion coefficient that scales as $(M/Q)^{\alpha}$, they found $\alpha = 0.8$ to 2.7. Following Droege [17], Cohen et al. related the value of α to the spectrum of interplanetary turbulence (taken to be a power-law in wave number, k^{-q}). They concluded that SEP spectral breaks in these events were organized by wave spectra in the range from $k^{-1.2}$ to $k^{0.7}$ (see also [2]), significantly flatter than a $k^{-5/3}$ Kolmogorov spectrum, consistent with a source of turbulence near the shock where the ions were accelerated. It is interesting that calculations by NRT [13] show that proton-amplified Alfven waves in SEP events can produce broad features in the wave spectra with $q \approx 0$, and that similar wave spectra have been reported in SEP events at 1 AU [14, 15].

Finally, we point out that the nature of spectra beyond the breaks has space-weather implications. The Band et al. form fits the Halloween spectra better than the Ellison-Ramaty form [2], and a power-law above the break is clearly required for the Jan. 20, 2005 event. Extrapolating these spectral forms results in significantly different estimates of SEP radiation doses, especially behind several g/cm^2 of shielding. It is therefore important to continue efforts to understand and eventually forecast not only the location of spectral breaks, but also the nature of the spectra beyond the breaks.

ACKNOWLEDGMENTS

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