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Solar Energetic Particle Spectra and Composition in the October/November 2003 Events

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The series of extremely large solar energetic particle (SEP) events of October and November 2003 were well observed by many spacecraft. We have combined data from the ULEIS and SIS instruments on ACE to obtain particle intensities over >3 decades in energy. The event-integrated composition (carbon through iron) not only varies from event to event, but also as a function of energy within an SEP event. These compositional variations are a result of the element-dependent spectral breaks and we suggest they can be substantially reduced when the spectra are examined in terms of rigidity-dependent escape from the shock.

1. Introduction

In late October and early November 2003 a series of solar flares and coronal mass ejections gave rise to several extremely large solar energetic particle (SEP) events. At energies above ~10 MeV/nucleon, 5 events are readily identified in the oxygen intensity time profiles [1]. We have combined data from the ULEIS [2] and SIS [3] instruments on the ACE spacecraft to obtain the spectra of heavy ions (carbon through iron) from ~0.1 to 100 MeV/nucleon. The time periods selected were energy-dependent to account for velocity dispersion and are given (for 3 energies) in Table 1. The left panel of Figure 1 shows the event-integrated oxygen spectra for the 5 events. It is clear that the events differed in intensity as well as in spectral shape. While a gradual steepening of the spectra (or 'spectral break') is apparent in each event, the energy at which this occurs varies from near 1 MeV/nucleon (for 26 October) to above 10 MeV/nucleon (for 28 October). Additionally, 4 of the 5 spectra are nearly power laws below the break, but with different spectral indices.

Not only is this variability seen in spectra of other elements, the position of the breaks, as well as the spectral character above and below the breaks, often differs for each element within the same event. This leads to energy-dependent composition, which is illustrated for Fe/O in the right panel of Figure 1 (n.b. the ratios have been scaled vertically for each event for clarity). Different measurement techniques used by ULEIS

Table 1. Selected Time Intervals for the 5 Events

≥ 7 MeV/nucleon		0.77 MeV/nucleon		0.1 MeV/nucleon	
Start Time	Stop Time	Start Time	Stop Time	Start Time	Stop Time
26 Oct 14:47	28 Oct 00:00	26 Oct 18:16	27 Oct 14:24	27 Oct 01:35	27 Oct 14:24
28 Oct 10:30	29 Oct 18:37	28 Oct 13:28	29 Oct 18:00	28 Oct 20:47	29 Oct 18:00
29 Oct 21:00	31 Oct 09:33	30 Oct 7:56	31 Oct 12:00	30 Oct 11:36	31 Oct 12:00
2 Nov 16:55	4 Nov 17:25	2 Nov 20:40	4 Nov 21:36	3 Nov 3:59	4 Nov 21:36
4 Nov 21:31	7 Nov 12:00	5 Nov 1:28	7 Nov 12:00	5 Nov 8:47	7 Nov 12:00

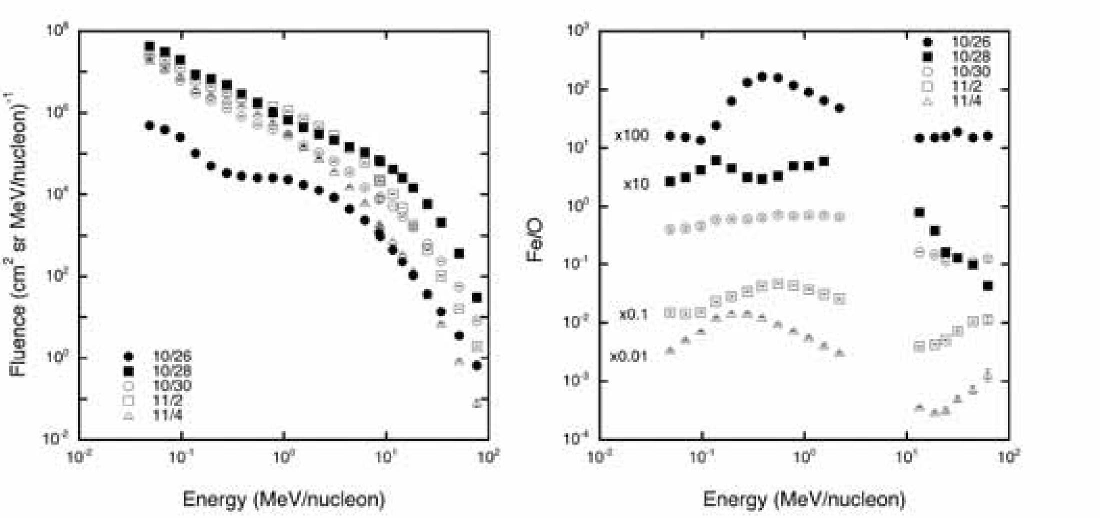

Figure 1. Oxygen fluence spectra (left) for the five October-November 2003 events and the Fe/O abundance ratios as a function of energy (right) for the five events. Note the Fe/O ratios are scaled by the factors given in the left side of the plot for clarity. The data gap in the Fe/O ratios is due to the different instrumental energy ranges of the ULEIS and SIS sensors for Fe.

(<3 MeV/nucleon) and SIS (>10 MeV/nucleon) lead to a gap in the energy coverage, yet the strong energy dependence of Fe/O is clear, with ratios above 10 MeV/nucleon being less than those observed near 1 MeV/nucleon - a result of the element-dependent spectral breaks. Interestingly, abundance enhancements and depletions (relative to average large SEP event composition at 1 MeV/nucleon [4]) as a function of element nuclear charge (Z) at 0.77 MeV/nucleon are not similar to those at 12-60 MeV/nucleon for any of the events [1]. For example, all the events are enhanced in Fe at 0.77 MeV/nucleon by factors of ~3 to 7.5, while at 12 MeV/nucleon 3 of the 5 events are depleted in Fe by more than a factor of 3 and the remaining events have nominal Fe/O ratios. Some ordering can be found for these variations when the abundances at high energies are normalized to those at low energies and examined as a function of Z (left panel of Figure 2). Here it is clear that the composition at 12 MeV/nucleon is systematically depleted relative to that at 0.77 MeV/nucleon for each event in an element-dependent manner. Although we do not have charge state measurements for all the elements in all 5 events, we use those reported in [5] to calculate the charge to mass ratio (Q/M) for each element and find that Q/M does organize the composition ratios well (right panel of Figure 2), suggesting that the spectral break energies (which cause the high- and low-energy composition differences) are related to rigidity-dependent effects in the shock acceleration or transport processes.

2. Diffusion Effects

Motivated by work on anomalous cosmic ray spectra [6], we suggest the breaks seen in the heavy ion spectra are primarily due to escape from the shock region. This has been expressed in terms of a diffusion coefficient [7], which is a function of a particle's mean free path. If we take the mean free path to be a power law in rigidity, or $(Mv/Q)^{\alpha}$, the diffusion coefficient, κ, can be expressed as

$$\kappa \sim (M/Q)^{\alpha}\,(E)^{(\alpha+1)/2}, \qquad (1)$$

where E is the particle energy per nucleon. Under the assumption that particles escape from the acceleration region near the shock at the same value of the diffusion coefficient, the spectral breaks for two different elements (1 and 2) should scale as

$$E_1/E_2 = [(Q/M)_1\,/\,(Q/M)_2]^{2\alpha/(\alpha+1)}. \qquad (2)$$

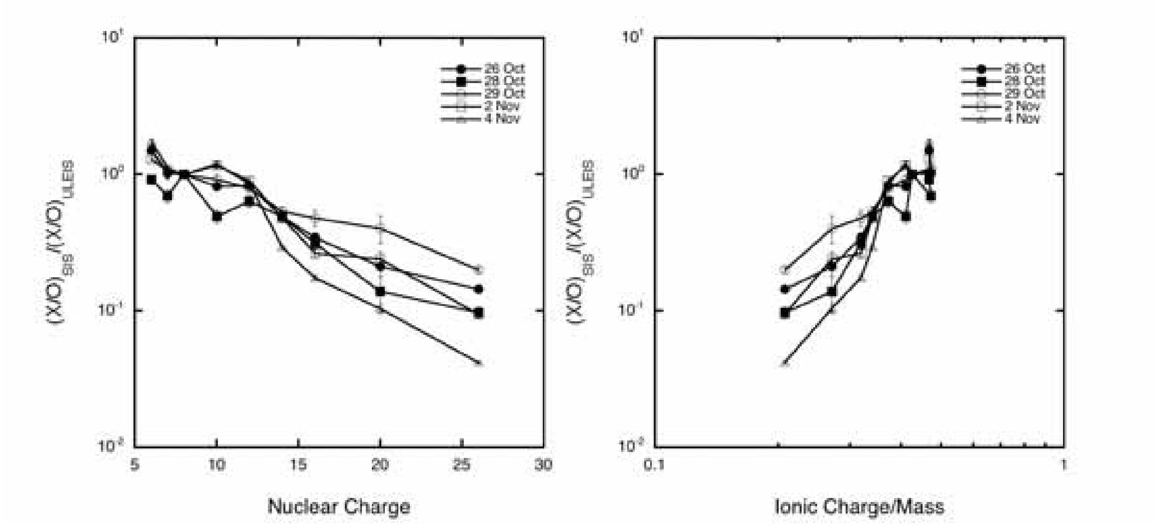

Figure 2. Abundances at 12-60 MeV/nucleon (from SIS, relative to oxygen) normalized by those at 0.77 MeV/nucleon (from ULEIS, relative to oxygen) versus nuclear charge (left) and charge/mass (right) of the elements for the 5 events.

Using the oxygen spectra as a template for each event, we have scaled the spectra of Ne, Mg, Si, S, Ca, and Fe in energy according to equation (2). A single value of α was selected for each event to produce abundance ratios relative to oxygen roughly independent of scaled energy. The Mg/O and Fe/O values versus scaled energy for each event are shown in Figure 3. Although some variation remains, it is much reduced compared to that in Figure 1, right panel. Although the scaling relationship in equation (2) is specifically only appropriate to the position of the spectral breaks and not the entire spectra, aligning the break points in this manner has the greatest influence in flattening the elemental ratios. Below the break points, we expect the spectra to be primarily determined by shock strength, not diffusion, and thus independent of Q/M [8] and not strongly affected by the energy scaling.

The value of α can be simply related to the spectrum of magnetic turbulence [9] if that is assumed to be a power law in wave number, or k^{-q}: $\alpha = 2-q$. The values of α we obtained for the 5 events were 1.0, 2.4, 1.3, 0.8, and 2.7 corresponding to wave spectra ranging from $k^{-1.2}$ to $k^{+0.7}$, all of which are significantly flatter than the dispersive region of the interplanetary turbulence spectrum (e.g., a Kolmogorov spectrum of $k^{-5/3}$). This is consistent with a source of turbulence existing near the shock region when the heavy ions were accelerated. Such flat (and even increasing) wave spectra were found to be a consequence of streaming energetic protons which amplify existing Alfven waves in the model of [10]. The calculated distortions are primarily located at wave numbers near to those resonant with 2.9 MeV/nucleon $Fe^{13.9+}$ ions [10], close to the break energies observed here, but also span approximately a factor of 10 in rigidity (or 100 in energy). Further observations of 'almost flat' wave spectra in the large July 2000 SEP event have recently been reported and are interpreted to be a consequence of proton-amplified Alfven waves upstream of a shock [11].

3. Conclusions

Although 4 of the 5 October/November 2003 SEP events were related to solar activity from the same active region as it crossed the solar disk [12], the event-integrated SEP spectra and composition exhibit distinctly different characteristics. This is apparent not only from one event to the next, but within an event from element to element when evaluated at common values of energy per nucleon. However, the spectra for most heavy ions appear to be more similar, resulting in nearly constant abundance ratios, when evaluated as a function of energy scaled according to the rigidity dependence of the ions' mean free paths. Although the

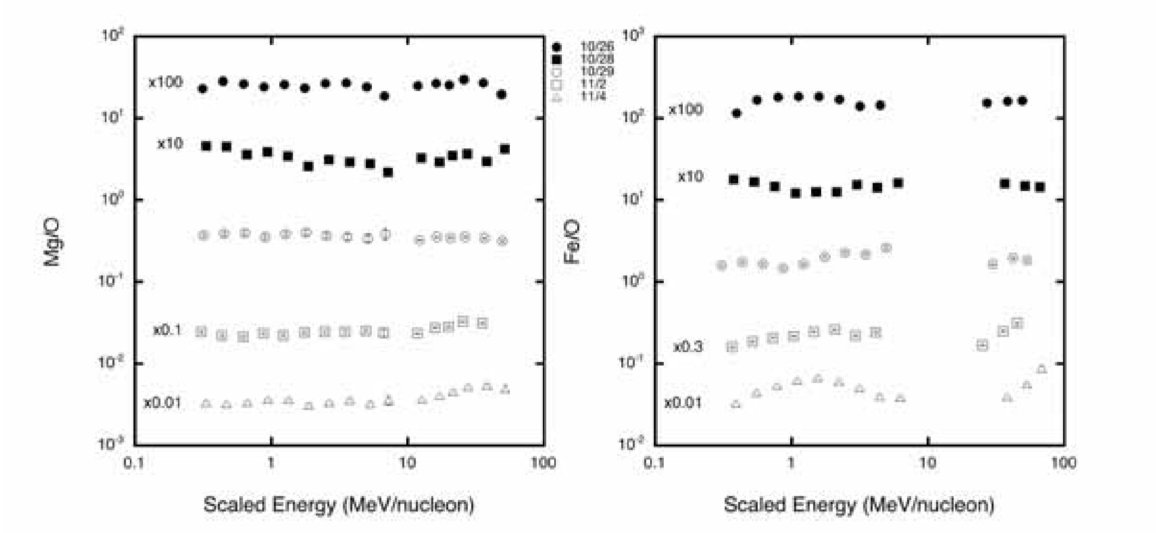

Figure 3. Mg/O (left) and Fe/O (right) abundance ratios resulting from the energy-scaled spectra for the 5 events.

assumptions made here are simple (non-energy dependent charge states and power-law rigidity dependences), the results indicate that SEP composition and spectra are perhaps best understood as a function of rigidity rather than kinetic energy.

Similar analysis has been done for H and He spectra, for which the charge states are known, in these same 5 events [13]. Although the values of α derived from that work are not identical to ours, with the exception of the 28 October event, nearly as good a correspondence between the H and He spectra can be obtained by using the heavy ion α values presented here. Accurate charge state information for heavy ions in SEP events (particularly as a function of energy) is key to further progress in this area and might also provide additional clues as to the origin(s) of the seed population(s) being accelerated.

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