Proton, Helium, and Electron Spectra during the Large Solar Particle Events of October, November 2003

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Abstract

The extraordinary period from late October through early November 2003 was marked by more than 40 coronal mass ejections, eight C-class flares, and five large solar energetic particle (SEP) events. Using data from instruments on the ACE, SAMPEX and GOES-11 spacecraft, the fluences of H, He, O, and electrons have been measured in these five events over the energy interval from ~0.1 to > 100 MeV/nucleon for the ions, and ~0.04 to 8 MeV for electrons. The H, He, and O spectra in these five events are found to resemble double power-laws, with a break in the spectral index between ~5 and ~50 MeV/nucleon which appears to depend on the charge-to-mass ratio of the species. Possible interpretations of the relative location of the H and He breaks are discussed. The electron spectra can also be characterized by double power laws, but incomplete coverage prevents an exact determination of where and how the spectra steepen. The proton and electron fluences in the 28 October 2003 SEP event are comparable to the largest observed during the previous solar maximum, and within a factor of 2 or 3 of the largest SEP events observed during the last 50 years. The two-week period covered by these observations accounted for ~20% of the high-energy solar-particle fluence over the years from 1997-2003. By integrating over the energy spectra, the total energy content of energetic protons, He and electrons in the interplanetary medium can be estimated. After correcting for the location of the events, it is found that the kinetic energy in energetic particles amounts to a significant fraction of the estimated CME kinetic energy, implying that shock acceleration must be relatively efficient in these events.

1. Introduction

The two week period including the last week of October, 2003 and the first week of November was marked by some of the most intense solar activity in the history of the space age, including 43 CMEs (see Gopalswamy et al. 2005), eight X-class flares, some of the largest solar particle events of this solar cycle, and two of the largest geomagnetic storms in history. Figures 1 and 2 summarize measured solar particle intensities of protons in several energy intervals. Five large solar energetic particle (SEP) events are evident in Figure 1, each associated with an X-class flare and a very fast CME. In the first four of these events the interplanetary shock was still accelerating particles to MeV energies when the shock reached 1 AU (see Figure 2). In addition, shocks associated with a number of other CMEs were observed during this period (see http://www.bartol.udel.edu/~chuck/ace/ACElists/obs_list.html).

These events were also marked by increases in the electron intensity at 1 AU, as shown in Figure 3. Electron increases were also observed in association with several of the interplanetary shocks. Table 1 summarizes key properties of the five large SEP events, which, for convenience, are sometimes referred to by number as Events 1 to 5.

The two largest of the solar particle events occurred on consecutive days, following an X17 flare on 28 October 2003 and X8.3 event on 29 October, both located near central meridian. Both events produced very fast CMEs, and in each case the interplanetary shocks from these events reached Earth within only ~19 hours. Upon arrival at 1 AU both shocks were still accelerating protons up to >15 MeV (see Figure 1).

The events of solar cycle 23 have been the best studied in history as a result of new instrumentation on spacecraft that include ACE, RHESSI, SAMPEX, SOHO, TRACE, Ulysses, and Wind. Many of the solar particle results have focused on new heavy ion measurements, obtained for the first time with excellent resolution, statistical accuracy, and energy coverage (e.g., Cohen et al. 2005). In order to complement these heavy ion data, we have made a concentrated effort to compile data from the most abundant species, H, He, and electrons – species that are often not well measured in instruments that are designed to extend to the iron group.

In this paper we report new observations of the energy spectra of H, He, O and electrons, integrated over each of the five largest SEP events during October, November 2003. These fluence spectra make use of data from five instruments on three separate spacecraft, the Advanced Composition Explorer (ACE), the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), and NOAA's 11th Geosynchronous, Operational, Environmental Satellite, GOES-11. Use of these five instruments makes it possible to cover the energy interval from ~0.1 MeV/nuc to several hundred MeV/nuc for H, 0.1 to ~80 MeV/nuc for He and O, and ~0.04 to 8 MeV for electrons.

Most of the observed spectra of H, He, and O in these five events are found to resemble double power-laws, with a break in the spectral index that occurs between ~5 and ~50 MeV/nucleon. Conventional spectral forms proposed for SEP events are not entirely adequate to fit all of these spectra, but improved fits have been obtained with a double-power-law form. The electron spectra can also be characterized by double power laws, but incomplete coverage prevents an exact determination of exactly where and how the spectra steepen. The observed H to He ratios vary considerably with energy, and also from event to event.

We find that both the proton and electron intensities in the 10/28/03 SEP event are comparable to the largest observed during the previous solar maximum, and within a factor of 2 or 3 of the largest SEP events observed during the last 50 years. The two-week period covered by these observations accounted for ~20% of the high-energy solar-particle fluence over the past seven years. By integrating over the observed energy spectra, the total energy content of energetic protons, He and electrons in the interplanetary medium can be estimated. After correcting for the location of the events, it is found that the kinetic energy in energetic particles amounts to a significant fraction of the estimated CME kinetic energy, implying that shock acceleration must be relatively efficient in these events.

2. Observations

2.1 Instrumentation

The observations reported here were drawn from the ULEIS, SIS, and EPAM instruments on ACE, the PET instrument on SAMPEX, and the EPS instrument on GOES-11. Table 1 summarizes the energy ranges over which H, He, O, and electron data were obtained. In this section we summarize briefly key features of the instruments and their location; additional details about the instruments and about corrections to the data can be found in the Appendix

The ACE spacecraft, in orbit about the inner LaGrangian point (L1) has its spin axis generally pointed within ~10° of the Sun (Stone et al. 1998a). The ULEIS (Mason et al. 1998) and SIS (Stone et al. 1998b) instruments are mounted at 25° and 60° to the spin axis, such that they scan the sunward hemisphere as the spacecraft spins, including the nominal ~45° (Parker spiral) angle of the average interplanetary magnetic field. The EPAM instrument on ACE has several telescopes with multiple look directions (see Appendix and Gold et al. 1998); in this study we use proton data from the LEMS120 telescope, mounted at 120° from the spin axis and looking in the hemisphere away from the Sun. Electron measurements from EPAM are from the LEMS30 telescope mounted at 30° to the spin axis.

The Proton-Electron Telescope (PET) is carried on SAMPEX in a ~600-km near-polar orbit. SAMPEX observes interplanetary particles directly only when over the polar caps. To avoid contamination from Earth's trapped radiation, the data presented here are restricted to times when SAMPEX was above 70° invariant latitude for ions, and above 75° for electrons. In addition, a cut was made to include only data taken when the PET telescope was pointed upward, within 40 degrees of the magnetic field direction.

Proton data from ~5 to 200 MeV, and He data from 1.3 to 125 MeV/nucleon were obtained from NOAA's GOES-11 satellite which is at geosynchronous altitude (GEO ≈ 6.6 Re). Proton data from the Energetic Particle Sensors (EPS) on the GOES satellites (Onsager et al. 1996) are available from http://spidr2.ngdc.noaa.gov/spidr/ in the form of "corrected integral intensities" (>1, >5. >10, >30, >50, >60. and >100 MeV) and also as "corrected differential intensities (eight energy intervals ranging from 0.8 - 4.2 MeV up to 200 – 500 MeV in the case of GOES-11). This study includes data from both of these data sets. Additional differential points were obtained by calculating differences between the hourly-average integral points (e.g., the difference between the >5 and >10 MeV intensities results in a differential intensity of 5 to 10 MeV protons). This procedure was also used by Tylka et al. (2004) to obtain SEP proton spectra. The results of this differencing technique are in good agreement with the corrected differential intensities, and we have plotted both sets of measurements (realizing that they are not independent). We have not used < 5 MeV GOES proton or He data because of the greater possibility of geomagnetic effects.

3. Observations

3.1 Selection of Time Periods

For the high-energy data from SIS and GOES the fluences were computed using hourly average intensities, starting with the first hour in which an increase above the pre-existing particle background was observed, and ending once the event had decayed to an extent that the integrated fluence was no longer increasing, or in some cases, when the next event began. The time intervals when the shock reached 1 AU were included. For PET, we included all polar passes that occurred within the time intervals established using GOES and SIS data. Table 2 includes the time intervals used for the high-energy fluences. These intervals are essentially the same as those used by Cohen et al. (2005) except for Event 1, where we used a longer time interval.

In most studies of SEP spectra, the fluences are computed for all energies over a single time interval. However, the extension of spectra to very low energies in the current study makes it necessary to take account of the fact that low-energy particles may arrive significantly later than higher-energy particles. Thus, when a new event is observed at high energies, particles near the lower end of our spectra (~0.1 MeV/nuc) may not arrive for another 12 hours or more. Picking a single time interval can thus result in the mixing of particles from more than one event. To avoid this, the start and stop times for the ULEIS and EPAM fluence calculations were adjusted to begin later than for higher energies. The high-energy onset used is the same as that used for SIS and PET, while at lower energies later onset times are chosen to increase as the inverse of the particle speed. Since most of the fluence arrives during the times of peak intensity, the details of these variable onset times do not have a significant influence on the reported fluences.

3.2 Integrated Fluence Spectra of Ions

The integrated fluence spectra of H, He, and O from these events are shown in Figure 4, plotted as a function of energy/nucleon. Note that all of the spectra have a power-law component at energies <1 MeV/nuc, with significant steepening in the energy range from ~10 to 50 MeV/nucleon. In those cases where there is sufficient data available at high energies, including all of the proton spectra, it appears that the high-energy spectra can also be represented as power-laws. These spectra are similar in shape to many of the gradual SEP events that have been measured over a broad energy interval (Mazur et al. 1992, Mason et al. 1998; Tylka et al. 2000, 2005), including, for example, the July 14, 2000 (Bastille Day) event (Smith et al. 2001, Tylka et al. 2001).

In some of the events in this study there is a clear difference in fluence between protons measured by ULEIS and EPAM. For each of these events we have examined the full 3-D proton angular distributions and determined that these differences are consistent with real differences in anisotropy. In those events showing a difference the EPAM protons measured by the LEMS120 telescope have a lower fluence than the protons measured by ULEIS (which points at 60° to the ACE spin axis) and the protons measured by the LEMS30 telescope have a greater fluence than those measured by ULEIS. This indicates that there is a greater fluence of protons from the solar direction than from the anti-solar direction, which may be due to an extended injection and acceleration of low energy protons in these events. An additional anisotropy involved at the lower energies that produces a higher fluence of protons from the solar direction is the Compton-Getting effect [Compton and Getting, 1935] as the fluence used in this study is in the spacecraft frame, not the solar wind frame. In some cases there are also differences in shape between the H, He, and O spectra.

In order to characterize these spectra further, we have fit them with several spectral shapes. Ellison and Ramaty (1985) proposed that solar particle spectra accelerated by shocks would have spectra of the form:

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

where J is the differential intensity, E is kinetic energy/nucleon, and K, E_o and γ are constants. This spectrum has a power-law shape at low energies, as expected from shock acceleration, with an exponential roll-over at high energies, presumably determined by the finite radius of the shock, or the available time for accelerating particles to high energy. Tylka et al. (2000, 2001) have found this spectral form to be useful in characterizing the spectra of a number of SEP events.

In Figure 5 we show the result of fitting the Ellison-Ramaty spectral form to these five events. In fitting these spectra over a broad energy interval, including data from several instruments, a 20% systematic uncertainty was added in quadrature with the statistical uncertainties (25% in the case of PET), which resulted in reduced chi-square values with a median value of 1.64. Table 4 includes the fitting parameters. The Ellison-Ramaty form can fit the low-energy portion of the spectra reasonably well, and it can also fit the breaks in the spectra. However, in a number of cases where the spectra extend to high energy, the fit rolls over too soon and does not fit the highest energy points (especially the proton spectra in Events 3 and 4).

Tylka et al. (2000, 2004; see also Mazur et al. 1992) have shown that spectral breaks in SEP events such as these are ordered by the charge-to-mass ratio of the species, and they considered E_o functions of the form $E_o \sim (Q/M)^b$, with b typically ≈ 1, but occasionally as large as $b \approx 2$. In these five events the $E_o(H)/E_o(He)$ ratios ranged from 1.2 to 2.0, with the last two events giving ratios very close to 2, as would be expected if b = 1. In all cases but one (oxygen in Event 1), we find $E_o(H) > E_o(He) \geq E_o(O)$.

The fact that the location of the spectral breaks is apparently ordered by Q/M suggests that the spectra might be better organized if plotted as a function of rigidity. In Figure 6, the data from the 2 November 2003 event have been plotted as differential rigidity spectra, assuming that Q(O) = 6.5. It in conceivable that in this representation the spectral breaks would occur at the same rigidity, but this was not the case in any of the five events.

The Ellison-Ramaty form fails to fit the highest-energy proton points in several of the events, and it appears that a double power-law representation might do a better job of fitting the spectra. In Figure 7 we show the results of fitting the H and He spectra with a spectral form developed by Band et al. (1993) to fit gamma-ray burst spectra, a form that has also been used by Tylka et al. (2005) to fit SEP spectra. The equation for this spectral shape is given by

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

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

where γ_a is the low-energy power-law slope and γ_b is the high-energy power-law slope and E and E_o are measured in energy/nucleon. The function is identical to the Ellison-Ramaty form below the transition energy, $(\gamma_b - \gamma_a)E_o$. At higher energies the function makes a smooth transition to a second power law. It is clear that this spectral form gives an improved fit to the high-energy spectra, and the median reduced Chi-square for the fits to H, He, and O was 1.15, compared to 1.64 for the Ellison-Ramaty form. The parameters of the fits to these events are summarized in Table 5.

The shapes of the spectra in Figure 7 are quite similar, as illustrated in Figure 8, which compares the fits to the five proton spectra. The 28 October 2003 event has the largest fluence below ~250 MeV, but at higher energies the spectral fits indicate that both Events 3 and 4 have harder spectra. Events 2, 3, and 4 were all prominent ground-level events recorded in a number of neutron-monitors (based on real-time data from the University of Delaware website. http://neutronm.bartol.udel.edu//Welcome.html).

3.3 H to He Ratios

From inspection of Figure 4 it is clear that the relative abundance of H and He vary with energy and from event to event. This is illustrated in Figure 9, which plots that H/He ratio as a function of time at ~10 MeV/nuc, and in Figure 10, where the H to He ratio is plotted as function of energy/nucleon. In each of these events the H/He ratio varies by a factor of ~3 to 50 from ~0.1 to ~100 MeV/nucleon (see also Mazur et al. 1993). There is no indication of a preference for the "coronal" ratio of H/He = 28 derived by Reames (1998) by summing a large number of SEP events at an energy of ~5 MeV/nucleon. The sudden change in the H/He ratio above ~10 MeV/nucleon in some of the events occurs because the break in the He spectra occurs at a lower energy/nucleon than the break in the H spectra (see Figures 5 and 7).

Also shown in Figure 10 is the H/He ratio obtained from fits to the spectra using the Ellison-Ramaty and Band et al. spectral shapes. Although both spectra fits can represent the transition in the ratio from low to high energy, they differ greatly at higher energies, with the extrapolated Ellison-Ramaty fits suggesting that the He/H ratio continues to increase more than is indicated by the extrapolated Band et al. fits. This difference may have relevance to the extrapolation of SEP spectra of heavier species.

The energy dependence of the He/H ratio raises the question of how one should characterize the relative abundance of H and He in SEPs. We suggest integrating the fluences of the species over energy to obtain the relative abundance of all observed accelerated particles. Table 6 includes the relative abundances of H, He, and O integrated from 0.1 to 100 MeV/nucleon. Note that except for the 28 October 2003 event, the H/He ratios are all ≈ 10, reasonably close to the photospheric H/He ratio of ~11.8 (Grevesse and Sauval 1998; Lodders 2003). Only the 28 October 2003 event has an integrated H/He ratio that is even close to the coronal abundance ratio of Reames (1998). The integrated He/O ratios vary by a factor of ~2.5, with three events reasonably close to the coronal value of H/He ≈ 57 (Reames 1998).

3.4 Integrated Fluence Spectra of Electrons

A plot of the electron intensities from 2 to 8 MeV in Figure 11 indicates significant intensity increases in the first four of these events, but a relatively smaller increase in the 11/4/04 event. The energy spectra derived at low energies from EPAM and at high energies from PET are shown in Figure 12. Both the low-energy and high-energy spectra are well represented by power-laws. The low-energy power-laws have $\gamma \approx -2$, while at >1.6 MeV the slope is more like –4. Because of the gap in the observations, it is difficult to determine where these spectra steepen. These low-energy spectra are similar in slope to those in Lin et al. (1982) below ~200 keV, while the high energy slopes are similar to those observed by Lin et al. (1982) above ~2 MeV and Moses et al. (1989) at even higher energies. In the study of Lin et al. (1982) and Lin (1985), the electron spectra were found to have a break around ~200 keV. Although the third and fourth spectral points in Figure 12 do indicate a steeper spectrum than the second and third points, the rather broad energy bins in Figure 12 make it difficult to compare these spectra in detail to those of Lin (1982) and Lin et al. (1985).

The absolute magnitude of the high-energy spectra in Events 2 and 3 is more uncertain, because of the very significant dead-time corrections that were needed at the times of maximum proton intensity. Indeed, during the early part of Event 3 (see Figure 11) the PET livetime decreased to a point where the electron intensity could not be reliably determined, and it was necessary to interpolate the intensity measurements to obtain the event-integrated. fluence. Note in Figure 11 that the intensity of Event 3 at MeV energies in PET appears to be significantly greater than that of Event 2, while at EPAM energies (Figure 3) these two events are of comparable intensity. We are confident that Event 3 is the larger of the two at high energies, but it is possible that during this period some fraction (<50%) of the events are due to chance coincidences between two lower-energy electrons that independently trigger the first two detectors in PET, thereby mimicking the signature of higher energy electrons. Although it appears that Event 3 has a harder spectrum throughout the course of the event, we have not shown the PET spectrum for this event because of the possibility that chance-coincidence background contributes during the highest intensity portions of the event. The electron fitting parameters for these events are summarized in Table 7, where the intensities are in units of electrons/cm^{2}sr-MeV.

Although the electron and proton spectral shapes are similar, the relationship between the electron and proton spectral indices is difficult to determine from this limited sample of five events. Lin et al. (1982) report on nine large well-connected flare events and find an electron spectral range (0.01 MeV < E < 0.2 MeV) between -1 and -2, consistent with this study. When we compare the low-energy electron spectral index (Figure 12) to the proton spectral index >30 MeV there is also a positive correlation, but the correlation is better between the spectral indices of the 1.8 – 8 MeV electrons and >30

MeV protons. Lin et al. (1982) selected only well-connected events, defined by flare locations between 30° and 90° solar longitude, while two of our events are near central meridian, which could introduce propagation effects. The five events in this study are an insufficient data base to study correlations of this kind, but we plan to extend these comparisons to additional events in the near future.

3.5 Total Particle Energy Content

The fluence measurements presented here can be used to estimate the total energy content of energetic solar particles in interplanetary space, as was recently done for the 21 April 2002 event by Emslie et al. (2004). Following the approach in Emslie et al, we have estimated the energy content of Events 1 – 5, as tabulated in Table 9. The first step is to calculate the total particle energy per unit area escaping into the outer solar system at the location of Earth, To do this we integrated the spectral fits in Figures 7 and 12 and over the energy interval from 0.01 to 1000 MeV/nucleon. This integration included corrections for the average number of times that particles of a given energy crossed 1 AU as a result of scattering on the interplanetary magnetic field. This correction was based on simulations by J. Giacalone (personal communication) and by G. Li (see also Li, Zank, and Rice 2003).

It is also necessary to take into account the fact that the observed SEP intensity at Earth depends on the longitude and latitude where the event originated, and to integrate over the total area over which solar particles escape into the outer heliosphere. As explained in Emslie et al. (2004), this integration is based on a semi-empirical model in which the maximum intensity is observed for events that originate at 0° longitude and 0° latitude. In this model, the intensities observed at Earth fall off exponentially with the latitude and longitude where the event originated, with e-folding angles ranging from 25° to 45° (based on observations from GOES and ACE). By integrating over a 1-AU sphere centered on the Sun, it is possible to relate the observed fluence at Earth to the total energy content of accelerated particles in interplanetary space.

The results in Table 9 show that four of the events during this time period involved total particle energies in excess of 10^{31} ergs, comparable to the 4/21/02 event studied by Emslie et al. (2004) (Note that the entry for the 4/21/04 event in Table 6 is ~50% larger than reported in Emslie et al. as a result of a correction of a numerical error in the integration procedure, and as the result of an improved representation of the low-energy proton fluence spectrum.)

All of the events in Table 9 that total more than 10^{31} ergs involved CME velocities >2000 km/sec. Although the observed fluences at Earth in the 11/2/03 and 11/4/03 events were significantly smaller than those for the 10/28 event, they were less favorably located (see Table 1) and the respective longitude corrections were factors of 2.4 and 4.9 times greater than for the centrally-located 10/28 event. There was a surprising amount of variation in these six events: the protons accounted for anywhere from 64% to 83%, of the energy content, He varied from 8% to 19%, Z>2 nuclei from 2% to 9%, and the electron contribution ranged from ~1% to ~20%, with the largest contribution in Event 3.

In Emslie et al. (2004) it was estimated that the absolute uncertainty in these estimates could be as large as a factor of 5, mainly as a result of uncertainties in the SEP latitude and longitude distributions, but also because of uncertainties in the correction for how many times particles cross 1 AU. The uncertainties in Table 8 were estimated by taking the square root of the multiplicative correction factor for multiple crossings of 1 AU, and adding this in quadrature with the square root of the correction factor for latitude and longitude (thus, a factor of 4 correction is assumed to have a factor of 2 uncertainty). The event-to-event uncertainty should be smaller than these estimates. Estimates of the total energy based on ACE alone should be more accurate for events that originate near central meridian. Multi-spacecraft measurements using the two STEREO spacecraft along with ACE could substantially reduce these uncertainties in the future.

3.6 Measurements of the ^{3}He/^{4}He Ratio

Although ^{3}He is rare on the Sun, it has long been known that impulsive solar flares sometimes show enhancements of ^{3}He/^{4}He up to 10^4 times the solar value (e.g. Reames 1999). In large, CME-associated events such as the ones considered in this paper, significant enrichments of ^{3}He/^{4}He by factors of ~10 to ~100 are also often seen [e.g. Cohen et al. (1999), Mason et al. (1999, 2002)].

Table 7.1 shows the ^{3}He/^{4}He ratios for the events in this study. Data in the lower energy range are from ULEIS, while data from the higher energy range are from SIS. Event 1 shows a factor of ~5 enrichment over the solar wind value in both energy ranges, similar to several other particle events reported in Mason et al. (1999), Cohen et al. (1999) and Wiedenbeck et al. (2000). The upper limits for Event 2 are rather high, due to the high background in this event, the most intense of the group. Similarly, the He isotope resolution in SIS is also broadened in Events 3 and 4 by the relatively high count rates. Events 3-5 have upper limits at 1 MeV/nucleon of 1.5 - 2 times the solar wind value

Mason et al. (1999) argued that significant enrichments of ^{3}He in CME-related particle events were due to re-acceleration of ^{3}He from impulsive flares by the CME-driven shock. This association was made on a statistical basis. For the current set of events we note that there was significant ^{3}He from impulsive events present at 1 AU essentially continuously from Oct. 22 through the onset of Event 1 on Oct 26. This may be the reason why the first event shows significant ^{3}He. The later events, for which the interplanetary medium was now filled with CME-accelerated material, would be expected to have little, if any, enhancement of ^{3}He, consistent with the observations.

3.7 The October-November Events in the Context of Solar Cycle 23

This past solar maximum has been one of the more active of the space age. Figures 13, 14, and 15 illustrate that the 28 October 2003 event was among the 3 or 4 largest for both ~1 MeV and ~50 MeV protons, and for 3 to 15 MeV electrons, comparable in intensity to the well-known 14 July 2000 (Bastille Day) event. Note that in the 40 to 80 MeV interval there are only seven events of this solar cycle with an intensity within a factor of 10 of the Bastille Day event, while at ~1 MeV there are many large events, including 15-20 with intensities within a factor of ten of the Bastille Day event. There are simply many more big events at low energy than at high energy. This is further illustrated by the integral intensities shown in Figure 16. At ~1 MeV the intensity builds up rather slowly over the solar cycle in a series of many small steps (see also Mewaldt et al. 2001). The Bastille Day event accounts for ~10% of the solar cycle fluence at 1 MeV, while the series of October-November events accounts for ~15%. In the 40 to 80 MeV interval there is a series of larger steps, including three (the Bastille day event, the November 2001 event, and the 28 October 2003 event) that each account for ~20% of the solar-cycle fluence.

The 28 October 2003event is one of the largest SEP events of the past 50 years (see, e.g., http://umbra.nascom.nasa.gov/SEP/seps.html). Figure 17 compares the spectra of the 28 October 2003 events with some of the largest of this solar cycle. The 28 October 2003event is very similar in spectral shape and in intensity to the Bastille Day event that also originated near central meridian, where most of the largest SEP events in the past 30 years have originated. Indeed, four of the five events in Figure 16 have very similar spectral shapes, only the February 1956 event stands out because of its much harder spectrum (note that this event is based on balloon-borne and neutron monitor measurements).

4. Discussion

It is interesting that all of the spectra in these five events can be represented by a common spectral shape – the double power-law with a break at energies that varies from a few MeV/nucleon to ~50 MeV/nucleon. The spectra of $Z \geq 6$ nuclei in these events can also be represented this way (Cohen et al. 2005). These spectral shapes are reminiscent of the spectra that result from the model of Zank et al. (2001; see their Figure 9) and Li et al. (2005). These authors suggest that in their model the spectral breaks occur at the maximum energy to which the shock can accelerate particles, after which the acceleration efficiency drops significantly. In those events where most of the fluence is associated with the passage of the CME-driven shock, the break in the fluence spectrum is expected to correspond to the maximum energy to which the shock can accelerate particles at 1 AU (Li et al. 2005). This maximum energy is determined by the spectrum of turbulence in region of the shock, where the turbulence is caused by the waves generated by particles escaping from the shock (Lee, 1983). Li, Zank, and Rice predict that the location of the breaks should scale as $(Q/M)^2$, with the breaks occurring at higher energy for species with greater Q/M values.

On the other hand Cohen et al. (2005) suggest that the breaks in the spectra are most likely related to diffusion effects, and they suggest that relative positions of the breaks for different species should scale according to the diffusion coefficients, $\kappa = 1/3\ v\ \lambda$, where v is the particle velocity and λ is the mean free path. Assuming that λ is a power law in rigidity, or $(Mv/Q)^\alpha$, and that the breaks occur at the same values of the diffusion coefficient, they find the following scaling in energy between one element and another:

$$E_1/E_2 = [(Q/M)_1 / (Q/M)_2]^{2\alpha/(\alpha+1)} \quad (3)$$

Using this relationship, Cohen et al. compared the spectra of seven species from O to Fe. Using average values of Q/M derived from <1 MeV/nucleon data, they found α values ranging from 0.8 to 2.7 for these five events, corresponding to Q/M scaling that ranged from $(Q/M)^{0.9}$ to $(Q/M)^{1.46}$.

It is of interest to see if the breaks in the H and He spectra in these five events follow $(Q/M)^2$, as suggested by Li, Zank, and Rice (2005), or follow the scaling found by Cohen et al. (2005). We have examined the relative location of the breaks for H and He in several ways. One measure of the break energy is the E_o value derived from fitting the Ellison-Ramaty spectral form (Table 4). If we compare the E_o values for H and He, we find that E_o for H ranges from 1.2 to 2 times that for He for these five events. Based on the suggestion of Li, Zank, and Rice (2005), we might have expected E_o for H to be 4 times that for He since the ratio of their Q/M ratios is 2.

We have also investigated the amount of energy shift in the He spectra that is required to minimize the variation in the He/H ratio. To determine this quantitatively we used the results of the double-power-law fits to the spectra (Figure 7 and Table 4), and restricted our attention to the energy range from 1 to 100 MeV/nucleon that is more or less centered on the breaks. Using this method, and comparing energy shifts of the form $E^{0.1n}$, with n an integer, we found that the optimum shifts ranged from x1.6 to x2.5, corresponding to α values ranging from ~0.5 to ~2.

In Figure 18 the proton spectra have been scaled down in energy by the amount indicated in the lower left hand corner (and adjusted in intensity) so as to compare the proton shapes to both the measured and fit He spectra. Note that the agreement is essentially exact in Events 2, 4, and 5, while there are some differences evident in Events 1 and 3 (these differences would be anticipated just from inspection of Figure 7). For Events 1 to 5, respectively, we find α = 0.5, 0.5, 2, 2, and 1.4, respectively, while Cohen et al. find α = 1, 2,4, 1.3, 0.8, and 2.7. Comparing these values, and the resulting energy shifts, we find that there is a significant discrepancy only for Event 2, where Cohen et al. found α = 2.7, and we find $\alpha \sim 0.5$. In all but this case, the shifts derived from the α values of Cohen et al. would lead to a reasonable, if not optimum, correspondence between the H and He spectral shapes.

A comparison of the H/He ratios for the five events is shown in Figure 19, plotted versus energy, rigidity, and versus energy after scaling the He spectrum up by the shift-factors chosen to minimize the percentage variation in the H/He ratio as a function of energy/nucleon (see Figure 18). Plotting the spectra as rigidity spectra has minimal effect on the variation of H/He, but shifting the He spectra by the amounts indicated in Figure 18 reduces the amount of variation substantially.

Mewaldt et al. (2005) have examined the location of the break energies for nine species ranging from H to Fe, and compared this energy to the charge-to-mass ratio of the ions as measured by SAMPEX. During the period just following shock passage in the 28 October event, the break energies for $1 \leq Z \leq 26$ nuclei could be fit by $(Q/M)^b$ with $b \approx 1.4$, while $b \approx 1.5$ if protons were not included. In the 29 October 2003 event, the break energies showed very little dependence on Q/M. It is possible that the spectra in this event were influenced by the fact that this event was launched into a medium that was already highly turbulent as a result of the larger event the occurred just 30 hours earlier.

This comparison of the H and He spectral shapes seems to favor the interpretation of Cohen et al. (2005), in which the Q/M-scaling of the spectral breaks varies from event to event, and is possibly governed by diffusion, over the interpretation of Li, Zank, and Rice (2005), which predicts $(Q/M)^2$ scaling. However, it is also possible that the proton spectra in these large events are influenced by the fact that protons are responsible for most of the turbulence. Maybe protons do not follow the scaling of heavier ions because they are not test particles.

It is of interest to compare the total energy content of the SEPs observed in these events with the total kinetic energy of the CMEs, which have been summarized in a paper by Gopalswamy et al. (2005). This comparison is shown in Figure 20. Note that the SEP energies range from ~0.6% to 24% of the CME kinetic energies, similar to the 21 April 2002 event analyzed by Emslie et al. (2004). If we assume that the energy content of the particles comes mainly from particle acceleration at the CME-driven shock, we can conclude that the shock acceleration process has a variable efficiency, that can at times be must be very efficient, such that the production of energetic particles sometimes extracts a reasonably large percentage (≥10%) of the CME kinetic energy. It is interesting that galactic cosmic rays apparently extract a similar fraction of the kinetic energy from supernova shocks in order to sustain the energy density of cosmic rays in the Galaxy (~1 eV/cm^3) over the average cosmic-ray lifetime of ~15 million years. (Yanasak et al. 2001).

Of course, it is also possible that some of the observed particles were accelerated at the flare site by other energy sources (see, e.g., Cane et al. 2003), or that some flare-accelerated particles were further accelerated by the shock (Li et al. 2003; Mewaldt et al. 2003). In these cases, the efficiency estimates could be reduced to some extent. Of course, the uncertainties in the comparison in Figure 20 are still rather large. However, these five events all involved very fast CMEs, and they originated over a range of longitudes. The uncertainties in the CME kinetic-energy estimates are minimized for those events that originated near the limb (M. Gopalswamy and A. Vourlidas, personal communication), while the uncertainties in the SEP estimates are minimized for events that originated near the central meridian. We hope to extend this study to a number of additional events in the near future.

5. Summary

By combining data from five instruments on three different spacecraft, this study has produced measurements of H, He, and O spectra extending from ~0.1 to 100 MeV/nucleon, including five large SEP events within a nine-day span. The energetic particle fluences during this period constituted a significant fraction of solar particle production during solar cycle 23 - anywhere from ~10% to ~25%, depending on energy. The 28 October 2003 event, in particular was comparable in fluence to some of the largest events observed during the space age.

The spectral shapes in all five events can be represented as double power laws, with low-energy slopes ranging from –1 to –1.5, and high energy slopes that typically ranged from –3 to –5. The transition between these power laws occurs between ~5 and ~50 MeV/nucleon. The double-power-law representation of Band et al. (1993) was found to provide a better fit to these spectra than the more conventional spectral form due to Ellison and Ramaty (1985). This shape is also characteristic of several of the other large events of the last 50 years.

In all cases the breaks in the H spectra occurred at higher energies than the breaks in the He and oxygen spectra. In the CME-driven shock-acceleration model of Li, Zank, and Rice, the location of such breaks is expected to scale as $(Q/M)^2$ implying a factor of four difference in energy for H and He. The observed difference in the break energies, determined by shifting the individual H and He spectra in energy until they matched, amounted to more like a factor of 2 ± 0.5. However, it is also possible that the model of Li, Zank, and Rice does not apply in these large events because protons may not act as test particles, because it is the protons that are responsible for producing most of the turbulence that is essential to the shock acceleration process.

The difference in the H and He break energies can also be interpreted as a result of diffusive processes, as proposed by Cohen et al. (2005). In this case the typical factor of two difference in break energies can be interpreted as arising from a diffusion coefficient that scales as $(Q/M)^{\alpha}$, with $\alpha \approx 1$.

The electron spectra in these events can also be represented as double power-laws, with low-energy spectral indices of –2 and high-energy indices of –4, consistent with earlier studies. Electrons accounted for anywhere from ~1% to 20% of the accelerated particle energy in these events. It will require a larger sample of events to explore how the electron and ion spectral shapes may be related.

The He/H ratio in these events varied by a factor of ~5 to ~20 with energy. The total abundance of H and He integrated from ~0.1 to 100 MeV/nucleon varied from ~9 to 30, with four events comparable to the photospheric ratio of 11.8, and only one comparable to the coronal value of 28.

Four of the five CMEs responsible for these events had velocities greater than 2000 km/sec and all five were still accelerating particles by the time they reached 1 AU. In all five events the estimated energy content of accelerated interplanetary particles amounted to $\sim 10^{31}$ ergs, accounting for a significant fraction (~0.6% to 24%) of the kinetic energy of the associated CMEs. Although there are uncertainties in these estimates, it appears that shock acceleration by CME-driven shocks is a surprisingly efficient process.

In the next few months we plan to extend the studies in this paper to a number of other large events from solar cycle 23.

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Appendix – Instrument Descriptions and Data Analysis Issues

In this Appendix we provide a more complete description of the five instruments used in this study. We also discuss some of the inter-calibration issues that arose in trying to combine data from these instruments during some of the largest SEP events of this solar maximum.

Ion measurements in the range ~0.1 to 8 MeV/nucleon were made using the Ultra-Low Energy Isotope Spectrometer (ULEIS) on ACE (Mason et al. 1998). ULEIS is a time-of-flight mass spectrometer that identifies ion mass and energy by measuring the time-of-flight of ions over a 0.5m flight path along with the kinetic energy deposited by the ion in an array of solid state detectors. The instrument design emphasizes a combination of high resolution and large geometrical factor (~1 cm^2sr). Although the triggering efficiency of ULEIS is ~100% for C and heavier ions, H and He have low efficiencies. These efficiencies were determined pre-launch at accelerator runs, but require re-calibration in flight due to losses in microchannel plate gain that are compensated from time to time by increasing the high voltage bias on the plates. During the events discussed here, the peak efficiency at 200 keV/nucleon was ~2% for H and ~15% for He, decreasing at higher energies. The ULEIS H efficiency used here was obtained from an inter-calibration of ULEIS and EPAM H intensities during the SEP event of 24 August 2002, when anisotropies were low. The ULEIS He efficiency for the events in this paper was based on direct comparisons with SIS high energy He, and at lower energies by assuming similar ULEIS He and O spectra during portions of the decay phase of 7 gradual SEP events observed between 22 April 2002 and 2 December 2003. (The assumption of spectral similarity during such periods is based on invariance of spectra late in gradual SEP events (Reames et al. 1997)

During periods of very high intensity such as those considered in this paper, instrument saturation and dead time issues are a potential problem. These were largely avoided during this period by the instrument's automated door, which automatically closes off portions of the aperture depending on particle count rates in the telescope. For event 1, the door was 100% open; for events 2, 3, and 4, it was at its 1% open setting; for event 5 it was at its 6% open setting. The 10/26 event was of moderate intensity and so presented no problems, and the subsequent door closures prevented saturation or dead time problems in events 3, 4, and 5. However, high-energy particles penetrating the telescope walls during much of Event 2 led to very high count rates even though the door was at its 1% open setting. Between approximately 10:20 UT on Nov. 28 through 13:00 UT on Nov. 29 ULEIS had significant dead time, which peaked at just over 80% between 22:30 on Nov. 28 and 03:30 on Nov 29. The dead time correction for ULEIS was obtained by comparing oxygen intensities with SIS oxygen intensities in overlapping energy intervals.

The Solar Isotope Spectrometer (SIS) onboard ACE consists of two identical silicon solid-state detector telescopes with a combined geometry factor of 38 cm^2sr (Stone et al. 1998a). SIS measures the elemental and isotopic composition of particles with atomic number Z between 2 and 30 with energies of ~10 to ~100 MeV/nucleon using the dE/dx versus residual energy technique.

The SIS instrument is mounted on the top (sunward-facing) deck of ACE with its boresight tilted 25 degrees from the normal to the deck. The spacecraft rotates with a ~12 s period about this normal, and SIS has a 95° full-angle field of view, so during each rotation SIS views particles within a 145°-wide cone centered on the spin axis. During ACE's orbit about the L1 Lagrange point, the spin axis is pointed to within ~5° to 15° of the Sun. Thus, for example, when the interplanetary magnetic field direction is at its nominal ~45° angle from the spacecraft-Sun line, the field direction is at least 17.5° (and often as much as 37.5°) inside the edge of the spin-averaged field of view of SIS.

SIS uses a priority system to select events to be preferentially telemetered during large SEP events, when the analyzed event rate often exceeds the telemetry capacity of ~10 events per second, and heavy (Z>3) nuclei are given higher priority than He. Furthermore, to minimize the instrument dead-time that the large flux of H and He would cause during large SEP events if all these particles were analyzed, a timer is started after the analysis of a He event to prevent the analysis of another such event for an adjustable period of time (typically ~10 seconds). This design deliberately throttles the throughput of He particles to a few percent of analyzed events under high-rate conditions. As a result, the livetime correction factors to obtain the He intensity can become quite large. The SIS and GOES-11 energy ranges for He overlap. During four of the events under study there was excellent agreement between SIS and GOES-11 He intensities, but during Event 2 (by far the largest during this period; see Figure 1) the He intensities measured by SIS were lower than those from GOES-11 by a factor of ~2.4. We have assumed that this discrepancy is due to an uncertainty in the He live-time in SIS, and corrected the SIS He fluences in Figure 4 to agree with those reported by GOES-11.

The Electron, Proton, and Alpha Monitor (EPAM) on ACE (Gold et al. 1998) is designed to measure ions (E > 40 keV) and electrons (E > 30 keV) from five separate solid-state detector (SSD) telescopes oriented to give nearly 4π pitch-angle coverage. Ion elemental abundances are determined by a ΔE vs. E telescope using a thin (4.8 μm) front detector in a three-component telescope. Two Low Energy Foil Spectrometers, LEFS60 pointing at 60° to the ACE spin axis and LEFS150 pointing at 150° to the spin axis, utilize a thin foil to prevent incident ions (E < 350 keV) from reaching the SSD while electrons can penetrate the foil with little energy loss. In the two Low Energy Magnetic Spectrometers, LEMS30 and LEMS120 pointing at 30° and 120° respectively, electrons below ~315 keV are swept away from the solid-state detectors by a rare-earth magnet. In the LEMS30 telescope these magnetically deflected electrons are counted by an additional SSD. This study uses ion measurements from the LEMS 120 telescope and electron measurements from the LEMS 30 telescope.

For large SEP events such as those in this study some electrons can scatter past the magnetic deflection system (at the ~5% level) and be falsely identified as low energy ions. This is readily identified during the onsets of SEP events when the intensity in some low-energy ion channels rises prior to what ion propagation from the Sun would allow. For the fluence measurements in this study, the low-energy ion fluence is dominated by the intensity around the time of the shock and electron contributions to the ion fluences are well below 1%.

The Proton/Electron Telescope (PET) was launched into a 600 km near-polar Earth orbit aboard SAMPEX in July 1992 (Cook et al., 1993). PET consists of twelve 2- to 3-mm thick silicon solid-state detectors grouped into eight functional units to form a multi-element telescope. Through a combination of range information in the stack and pulse-height information from the first three detectors, PET distinguishes protons, alphas, and electrons cleanly from one another, and provides energy spectra above 19 MeV/nuc for protons and alphas and electron spectra from ~1.6 to 8 MeV. Pulse-height information is telemetered for only a sample of particles entering the telescope. A multiple-dE/dx technique can be used to obtain energy spectra for ions that penetrate the entire detector stack; however, the need to use the pulse-height-analyzed sample to obtain spectra limits the statistic accuracy. Since H and He events are assigned the same priority, most of the ion events in the telemetry are protons, and it is not possible to obtain adequate statistics for the He spectrum beyond ~100 MeV/nuc.

Included in the PET telemetry is a "livetime" counter, used extensively to obtain corrections for instrument deadtime in the inner radiation belt (Looper et al., 1996), mostly due to the high count rate in the front detector. However, count rates over the poles during the largest SEP events are much greater than in the inner radiation zone, and PET intensities for the October-November events are found to be systematically lower than GOES and SIS measurements after correcting for deadtime in PET using our standard algorithms. Since deadtime affects measurements of all species and energies equally (as a common multiplicative factor), this problem does not impair measurements of spectral shape or of relative particle abundances, and therefore PET observations have simply been scaled upward by a factor that varies from event to event, in order to normalize PET observations with those from other instruments. These factors, independent of energy and species, varied from x2 in Event 4 event to x7 in Event 2, the most intense of this series. It is possible that other factors contributed to these discrepancies. For example, it is possible that PET measures lower SEP intensities due to geomagnetic effects [PET is at a much lower altitude (~600 km) than GOES-11 (~40,000 km)]. Perhaps SEPs do not always have access over the full view cone of PET (~50° full angle) over all portions of each polar pass.

The electron response of the PET instrument was calibrated prior to launch using accelerator and beta-spectrometer facilities covering electron energies from~0.5 to 30 MeV. This study includes events that trigger the first two or three PET detectors in coincidence. Calibration data in 16 energy intervals ranging from ~1.6 to 8 MeV were integrated over angles to provide omni-directional response functions. Flight data from invariant latitudes >75° were collected in the same energy intervals and averaged over each polar pass, thereby providing ~48 min time resolution. With interpolation between the polar passes, the data were integrated over the duration of each SEP event to obtain a fluence for each energy channel.

During times of intense solar protons a few of the electron channels are contaminated by a background of degraded proton signals (e.g., protons passing through the edge regions of the two front detectors, P1 and P2). An estimate of this background is obtained from energy channels without a normal electron response and subtracted from the data. A model electron fluence spectrum is constructed with 8 points logarithmically spaced in energy from 1.6 to 8 MeV and connected by power-law segments. This spectrum is combined with the calibrated response functions and integrated over energy to obtain simulated counts in each channel. The spectral points are then adjusted to obtain a least-squares fit between the simulated and observed counts, while simultaneously satisfying a smoothness constraint on the spectrum. The data points are weighted according the sum of the statistical uncertainties and an additional 20 per cent relative uncertainty on each point. The smoothness criterion and the additional relative uncertainty are required to overcome influences of systematic uncertainties in the instrumental response and in the background corrections. Uncertainties in the final spectral points are estimated by error propagation of the assumed weighting factors divided by the mean square mismatch between the simulated and observed data points in order to approximately account for systematic discrepancies.

At any given time there are usually SEP data available from two or more GOES satellites. In comparing the solar proton intensities reported by GOES-10 and GOES-11 in a number of large SEP events between 2000 and 2003, we found that GOES-10 measurements were systematically lower than those from GOES-11 by an energy dependent factor that was sometimes as large as ~2 at ~10-20 MeV, and less at higher energies. This study has been restricted to GOES data from GOES-11. The GOES-10 vehicle was inverted relative to the other GOES spacecraft because of a problem with its solar array (T. Onsager, personal communication 2001). The inversion forced the Energetic Particle Sensors on GOES-10 to look towards the east rather than the west. Thus, particles arriving from the east had guiding centers at altitudes below GOES-10. This resulted in a lower GOES-10 fluence at times because these particles must have reached the vehicle via more complex trajectories with mirror points below GEO. Even at 20 MeV, where the proton gyro-radius at GEO is approximately 1 Earth radius, the effective radial gradient of solar particles was sufficiently large to lower the integrated fluence measured at GOES-10.

We have not used differential intensities from GOES satellites greater than the 80 to 200 MeV channel (which we plot at ~120 MeV). We find that solar proton data in the 200 to 1000 MeV range from the GOES satellites are difficult to reconcile with a smooth extrapolation of the spectra observed below 100 MeV. We have also made use of He intensities from the same web site in five channels that span the range from 4 to 500 MeV (1 to 125 MeV/nucleon).

Table 1: Large Solar Proton Events during October-November 2003								
Event	Flare Date	Time	GOES-10 X-ray Flux	Location	CME Velocity (km/sec)	Peak >10 MeV Protons	Shock Date	Shock Time
1	10/26/03	17:21	X1.2	N04W43	1537	373	10/28	1:31
2	10/28/03	11:00	X17.2	S20E02	2459	25242	10/29	5:58
3	10/29/03	20:37	X10	S20W09	2029	2158	10/30	16:19
4	11/2/04	17:03	X8.3	S18W59	2598	1356	11/4	5:59
5	11/4/04	19:29	X28	S18W88	2657	303	11/6	19:19

Table 2: Instruments and Energy Coverage					
		Energy Range (MeV or MeV/nucleon)			
Instrument	**Spacecraft**	**Protons**	**Helium**	**Oxygen**	**Electrons**
ULEIS	ACE	0.16 – 7.2	0.11 – 7.2	0.04 – 9.7	
EPAM	ACE	0.047 –4.8			0.038 – 0.32
SIS	ACE		3.4 – 29.4	7.0 –90	
PET	SAMPEX	19 - 400	20 - 80		1.2 - 8
	GOES-11	- 200	1.3 to 125		

Table 3: Fluence Measurement Intervals				
Event Number	Flare Date	Onset Time	High-Energy SEP Start	High-Energy SEP End
1	10/26/03	17:21	1800 on 10/26	1000 on 10/28
2	10/28/03	11:00	1100 on 10/28	2000 on 10/29
3	10/29/03	20:37	2100 on 10/29	2400 on 10/31
4	11/2/04	17:03	1700 on 11/2	2000 on 11/4
5	11/4/04	19:29	2100 on 11/4	1200 on 11/7

Table 4: Ellison-Ramaty Fitting Parameters				
Event	Species	Normalization	Gamma	Eo
10/26/03	H	$3.20 \pm .19 \times 10^7$	-0.96 ± .04	15.0 ± 0.7
	He	$2.64 \pm .17 \times 10^6$	-1.26± .05	10.5 ± 1.0
	O	$2.43 \pm .15 \times 10^4$	-1.32 ± .04	13.2 ± 1.0
10/28/03	H	$1.35 \pm .09 \times 10^9$	-1.05 ± .04	28.2 ± 1.9
	He	$4.90 \pm .25 \times 10^7$	-1.00 ± .04	16.8 ± 0.9
	O	$1.06 \pm .05 \times 10^6$	-1.10 ± .04	13.9 ± 0.6
10/29/03	H	$2.98 \pm .18 \times 10^8$	-1.17 ± .04	33.1 ± 2.3
	He	$3.00 \pm .15 \times 10^7$	-1.52 ± .03	26.7 ± 2.5
	O	$2.67 \pm .14 \times 10^5$	-1.35 ± .03	16.3 ± 1.0
11/2/03	H	$4.34 \pm .27 \times 10^8$	-1.26 ± .04	20.2 ± 1.3
	He	$3.96 \pm .24 \times 10^7$	-1.36 ± .04	10.4 ± 0.9
	O	$9.88 \pm .63 \times 10^5$	-1.08 ± .04	6.25 ± .32
11/4/03	H	$1.39 \pm .08 \times 10^8$	-1.54 ± .04	22.9 ± 1.1
	He	$1.08 \pm .06 \times 10^7$	-1.62 ± .04	11.2 ± 0.8
	O	$2.34 \pm .16 \times 10^5$	-1.54 ± .03	6.66 ± .37

Table 5: Fitting Functions for Double Power-Law Spectra					
Event	Species	Normalization	Gamma1	Gamma2	Eo
10/26/03	H	$3.26 \pm .20 \times 10^7$	-0.87 ± .06	-4.68 ± 20	12.8 ± 1.08
	He	$3.01 \pm .24 \times 10^6$	-1.08 ± .08	-3.24 ± .20	6.86 ± 0.9
	O	$3.20 \pm .25 \times 10^4$	-1.04 ± .07	-3.52 ± .15	6.99 ± .93
10/28/03	H	$1.35 \pm .09 \times 10^9$	-1.04 ± .04	-4.57 ± .93	27.4 ± 2.6
	He	$4.93 \pm .16 \times 10^7$	-1.03 ± .02	-11.0 ± 3.5	17.9 ± 0.5
	O	$1.04 \pm .04 \times 10^6$	-1.12 ± .02	-7.0 ± 4.0	15.0 ± 0.3
10/29/03	H	$3.05 \pm .20 \times 10^8$	-1.10 ± .05	-3.15 ± .14	26.1 ± 3.0
	He	$2.99 \pm .17 \times 10^7$	-1.52 ± .04	-6.6 ± 7.7	27.4 ± 4.9
	O	$2.82 \pm .17 \times 10^5$	-1.31 ± .03	-4.09 ± 0.38	14.0 ± 1.5
11/2/03	H	$4.89 \pm .33 \times 10^8$	-1.09 ± .06	-3.44 ± .10	13.2 ± 1.5
	He	$4.75 \pm .33 \times 10^7$	-1.22 ± .05	-3.70 ± 0.14	7.09 ± 0.76
	O	$1.21 \pm .09 \times 10^6$	-0.95 ± .05	-4.67 ± .15	4.87 ± .37
11/4/03	H	$1.40 \pm .09 \times 10^8$	-1.52 ± .04	-4.86 ± .33	21.7 ± 1.5
	He	$1.09\pm .03 \times 10^7$	-1.62 ± .02	-5.06 ± 1.01	11.2 ± 0.3
	O	$3.77 \pm .34 \times 10^5$	-1.32 ± .05	-4.65 ± .12	3.90 ± .33

Table 6: Integrated Abundances from 0.1 to 100 MeV/nucleon		
Event	H/He	He/O
10/26/03	12.1	102
10/28/03	30.2	48
10/29/03	8.7	131
11/2/03	11.2	51
11/4/03	12.4	53

Table 7 - Fitting Parameters for Electron Spectra				
	EPAM (0.04 to 0.32 MeV)		PET (1.6 – 8 MeV)	
Event	Normalization	Spectral Slope	Normalization	Spectral Slope
10/26/03	1.15×10^{7}	-2.23	8.40×10^{6}	-4.19
10/28/03	6.75×10^{8}	-1.90	1.46×10^{8}	-4.27
10/29/03	7.40×10^{8}	-1.76		
11/2/03	9.75×10^{7}	-2.08	7.24×10^{7}	-3.68
11/4/03	1.08×10^{7}	-1.50	1.67×10^{7}	-3.98

Table 8 – ^{3}He/^{4}He Ratios		
Event	^{3}He/^{4}He (x10^{4}) (0.5-2 MeV/nuc)	^{3}He/^{4}He (x10^{4}) (5-14 MeV/nuc)
10/26/03	16 ± 8	29 ± 10
10/28/03	<32	<339
10/29/03	<9	<159
11/2/04	<7	<174
11/4/04	<6	<49

Table 9: Energy Content of Accelerated Interplanetary Particles				
Event	Location	CME velocity (km/sec)	CME Kinetic Energy (x 10^{31} ergs))	Total Interplanetary Particle Energy (x 10^{31} ergs)
10/26/03	N02W38	1537	24	0.14 +0.21, -0.08
10/28/03	S16E08	2459	64	5.9 +3.3, -2.1
10/29/03	S15W02	2029	34	1.4 +2.1 – 0.9
11/2/03	S14W56	2598	16	3.8 +8.4, -2.6
11/4/03	S19W83	2657	61	1.9 +5.8, -1.4
4/21/02	S14W84	2397	20	4.7 +11.6, -3.3

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