October/November 2003 interplanetary coronal mass ejections: ACE/EPAM solar energetic particle observations
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Received 29 November 2004; revised 15 April 2005; accepted 21 April 2005; published 13 August 2005.

In late October and early November 2003 the ACE spacecraft at 1 AU detected two shock-associated interplanetary coronal mass ejections (ICMEs). In the sheath region formed in front of both ICMEs, some of the highest speeds ever directly measured in the solar wind were observed. We analyze in detail the energetic particle signatures measured at 1 AU by the EPAM experiment on board ACE during the passage and in the vicinity of these ICMEs. Solar energetic particles (SEPs) are utilized as diagnostic tracers of the large-scale structure and topology of the interplanetary magnetic field (IMF) embedded within both ICME events. In order to explain the bidirectional particle flows observed within both ICMEs, we have examined two candidate scenarios for these ICMEs in terms of open and closed magnetic field configurations. In the context of an open field configuration, the enhanced magnetic field regions associated with the CME-driven shocks mirror the energetic particles and hence the observed bidirectional flows. In the context of a closed field configuration, bidirectional flows result from particle circulation and reflection in a looped field configuration. Furthermore, we use the ACE/EPAM observations to reassess the leading and trailing boundaries of the ICMEs with respect to those previously proposed based upon ACE/SWEPAM solar wind plasma, suprathermal electron measurements, and ACE/MAG magnetic field data.


1. Introduction

Using Skylab observations, Gosling et al. [1974] identified coronal mass ejections (CMEs) that appeared as large magnetic loops anchored near regions with strong magnetic fields at the solar surface, yet expanding outward through the solar corona. The interplanetary counterparts of CMEs are usually referred to as interplanetary CMEs (ICMEs) or ejecta. Common signatures of ICMEs include numerous features [e.g., Gosling, 2000, and references therein] such as counterstreaming suprathermal (>80 eV) electrons, strong and smoothly varying magnetic field strength, anomalously low solar wind proton and electron temperatures, low plasma beta conditions, low magnetic field variance, smooth magnetic field rotations characteristic of magnetic flux ropes (that correspond to a fraction of the total number of CMEs observed in the solar wind [see Richardson and Cane, 2004a]), solar wind helium abundance enhancements relative to protons, enhanced solar wind ion charge states, and enhancements in minor ion abundances [Richardson and Cane, 2004b]. As has been noted by many authors [e.g., Neugebauer and Goldstein, 1997], individual signatures may not be detected in all ICMEs either because they are not present or as a result of instrumental limitations or data gaps. Furthermore, even if several signatures are present in an ICME, they do not necessarily appear synchronized with each other. Thus to identify ICMEs, observations of as many signatures as possible should be considered; those that are more frequently present, such as proton temperature depressions or compositional signatures, are of particular value [Cane and Richardson, 2003].

Energetic particle signatures provide a useful tool to identify ICMEs [e.g., Richardson, 1997, and references therein]. Solar energetic particle (SEP) events observed in the ecliptic plane at 1 AU usually show ~1 MeV proton intensities peaking near the passage of shocks driven by fast CMEs [Cane et al., 1988]. The subsequent entry into the ICME is usually accompanied by a decrease in the particle...
Occasionally, bidirectional ~1 MeV ion flows (BIFs) may also be observed within the ICMEs [Marsden et al., 1987].

A series of intense solar flares and fast CMEs which have generated much interest in the space physics community were observed in late October and early November 2003, during the declining phase of solar cycle 23 [Lopez et al., 2004]. The physical consequences of these extreme events in terms of the energetic particle intensities measured in different regions of the heliosphere are documented in the work of Lario et al. [2005]. The associated SEP events were among the largest in solar cycle 23 as observed in the ecliptic plane and at a heliocentric distance of 1 AU [Cohen et al., 2005]. The purpose of this paper is to provide a detailed analysis of the energetic particle signatures detected at 1 AU by the ACE/EPAM experiment during the passage of two ICMEs preceded by extremely fast solar wind observed on 29 October and 30 October 2003 [Skoug et al., 2004].

SEPs are utilized in this paper as diagnostics of the large-scale structure and topology of the magnetic field embedded within both ICME events, and the important scientific question of whether the detected ICMEs have been detached from the solar corona or are still magnetically anchored to it when they arrive at 1 AU is addressed. Identification of the ICME leading and trailing edges is also investigated in the context of energetic particle observations with respect to those identified by Skoug et al. [2004]. A preliminary discussion of these observations was given by Malandraki et al. [2005].

2. Instrumentation

The Advanced Composition Explorer (ACE) spacecraft was launched in August 1997 and is in a halo orbit about the L1 Lagrangian point. In this paper, we use measurements of the angular distributions of the intensities of energetic electrons in the energy range 42–290 keV detected by the sunward looking telescope LEFS60 and the antisunward looking telescope LEFS150 of the EPAM experiment (Electron, Proton, and Alpha Monitor) on board ACE. The EPAM experiment (the flight spare of the Ulysses HI-SCALE instrument) has been described in full detail by Gold et al. [1998]. We also use 1.9–4.8 MeV ion data from the LEMS120 ion telescope. The spacecraft spin axis is directed within 20°
of the Sun. Furthermore, observations of magnetically deflected electrons (DE) in the energy range 38–315 keV measured by the B detector of the CA60 telescope of the EPAM experiment are also presented. The numbers 60, 120, and 150 denote the angle that the collimator centerline of the telescope makes with the spacecraft spin axis. Magnetic field and solar wind plasma observations at 1 AU were provided by the MAG and SWEPAM instruments on ACE, respectively [Smith et al., 1998; McComas et al., 1998]. SWEPAM data from 28 to 31 October exist only in a ~33 min time resolution [Skoug et al., 2004].

3. Observations and Data Analysis

[7] Figure 1 shows 1-min averaged differential intensities of 38–315 keV electrons in four energy channels (DE1–DE4) and 1.9–4.8 MeV ions measured by the ACE/EPAM experiment from 0000 UT on 28 October to 1200 UT on 3 November. Electron and ion intensity enhancements were observed in association with intense solar events or with the arrival of transient interplanetary structures as described below. Table 1 lists the solar flares and CMEs observed throughout this time interval and associated with electron intensity enhancements as seen by ACE. Information on solar activity is provided by the Solar Geophysical Data (http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp). CME parameters were taken from the SOHO/LASCO CME catalogue compiled by S. Yashiro and G. Michalek (available at http://cdaw.gsfc.nasa.gov/). The vertical arrows in Figure 1 indicate the time of observation of CMEs (short thick arrows) and the onset of the temporally associated soft X-ray flare emission (long thin arrows). The intense electron intensity enhancements observed following the occurrence of the X17 solar flare and the fast halo CME on 28 October (Table 1) are discussed in the work of Simnett [2005].

[8] Solar wind and magnetic field observations throughout the time interval shown in Figure 1 are described in the work of Skoug et al. [2004]. We refer the reader to this paper for further details on the analysis of transient flow structures that moved past ACE during this period. In Figure 1 we have indicated the passage of two shocks (solid vertical lines) at 0558 UT on 29 October (S1) and at 1619 UT on 30 October (S2). The shock S1 was followed by the passage of an ICME that according to Skoug et al. [2004] started at 0800 UT on 29 October and ended at 1600 UT on 30 October (first heavy solid bar at top of Figure 1). These authors used smooth rotations of the magnetic field to identify the passage of this first ICME. As described by Skoug et al. [2004], solar wind data were limited during this period (due to lack of He++ and electron measurements by the solar wind SWEPAM instrument) and exact timing and identification of this first ICME were difficult.

[9] A second electron intensity enhancement occurred late on 29 October in association with the X10 solar flare and associated fast halo CME. The onset of this new SEP event was detected when ACE was still within the first ICME. The shock S2 was followed by the passage of a second ICME that according to Skoug et al. [2004] started at 0200 UT on 31 October and ended at 1800 UT on 2 November (second heavy solid bar at top of Figure 1). The plasma and magnetic field signatures used by these authors to identify the passage of this second ICME were (1) smooth rotations of the magnetic field direction, (2) counterstreaming suprathermal (>80 eV) electrons, (3) a low proton temperature, and (4) a helium abundance enhancement relative to protons. These signatures, however, indicate different times for the trailing edge of this ICME [see Skoug et al., 2004, Figure 3]. In the following we analyze in detail the energetic particle signatures measured during the passage of these two ICMEs. On the basis of these energetic particle observations, we determine the times that the boundaries of the two ICMEs moved past the ACE spacecraft (indicated by the vertical dashed lines in Figure 1).

3.1. First ICME, 29–30 October 2003

[10] Figure 2 shows energetic ion, near-relativistic electron, solar wind, and magnetic field observations by the EPAM, SWEPAM, and MAG experiments on board ACE during the passage of the first ICME over the spacecraft. After the passage of the shock S1, a period with turbulent enhanced magnetic field was observed, briefly reaching a peak value of 68 nT (indicated by a triangle in the fourth panel from the top of Figure 2). Very high values of the solar wind speeds were measured in the sheath region formed downstream of the shock S1 and in front of the first CME by the SWEPAM and SWICS instruments on ACE [Skoug et al., 2004; Zurbuchen et al., 2004]. SWICS measured values up to 1900 km/s [Zurbuchen et al., 2004], whereas the maximum solar wind speed measured by SWEPAM was of the order of 2000 km/s [Skoug et al., 2004] (see also Figure 2).

[11] On the basis of the observed magnetic field and energetic particle signatures, we argue that the two vertical dashed lines in Figure 2 at 1100 UT on 29 October and 0855 UT on 30 October denote a more accurate determination of the boundaries of the first ICME than those boundaries identified by Skoug et al. [2004]. Smooth rotations of the magnetic field direction began to be observed at the time of the first vertical dashed line [see also Kuwabara et al., 2004]. Furthermore, at that time, there is a change in B from high to low variance in both magnitude and direction, a typical magnetic field signature of ejecta [e.g., Gosling, 1997], as well as a decrease in the ~MeV ion intensity [e.g., Richardson, 1997]. It is important to note, however, that the entry of ACE into the ICME was associated with an
Figure 2. (main panel from top to bottom) Ion, electron, solar wind, and magnetic field observations by the EPAM, SWEPAM, and MAG experiments on board ACE during the passage of the first ICME (29–30 October). The solid vertical lines identify the passage of the shocks S1 and S2. The black horizontal bar in the top panel indicates the time interval identified by Skoug et al. [2004] as the first ICME. The dashed vertical lines indicate our identification of the boundaries of the ICME. The black triangle in the fourth panel identifies the period with the highest (68 nT) magnetic field magnitude. (right panels) The 64–112 keV electron pitch-angle distributions (PADs) measured by the LEFS60 and LEFS150 telescopes of the EPAM instrument [Gold et al., 1998]. (bottom panels) The 1.9–4.8 MeV ion PAD snapshots as observed by the eight sectors of the LEMS120 telescope.
increase of the electron intensity, accompanied by a magnetic discontinuity at this boundary.

[12] The trailing boundaries of ICMEs are usually more difficult to identify, and their determination is more subjective [Neugebauer and Goldstein, 1997]. Because of the uncertainties in the SWEPAM measurements [Skoug et al., 2004], energetic particle observations provide the required piece of information to determine the boundaries of this ICME. An abrupt increase in the low-energy ion intensity is observed at the time of the second vertical dashed line in Figure 2. Observations at 1 AU in the ecliptic plane usually show a recovery of ion intensities at or near the exit from an ejecta [Richardson, 1997]. However, in this event the situation is different due both to the occurrence of the second

Figure 3. From top to bottom are shown ion, electron, solar wind, and magnetic field observations from 1200 UT on 30 October to 0000 UT on 3 November by the EPAM, SWEPAM, and MAG experiments on board ACE during the passage of the second ICME. The solid vertical line identifies the passage of the shock S2. The black horizontal bar in the top panel indicates the time interval identified by Skoug et al. [2004] as the second ICME. The dashed vertical lines indicate our identification of the boundaries of the ICME.
SEP event late on 29 October within the passage of the ICME (see Figure 1) and to the proximity of the shock S2 traveling behind the ICME. Figures 2a to 2e show the 64–112 keV electron pitch-angle distributions (PADs) during the onset of the second electron event. Normalized differential intensity is plotted versus pitch angle. On top of each panel, S indicates the maximal differential intensity to which the distribution is normalized (in units of counts/(cm² s sr MeV)). The letters a to e correspond to the times indicated by the same letters in the second panel from the top of the time-intensity electron plot in the left-hand side of the figure. The electron fluxes were observed to rise simultaneously at all energies at 2145 UT on 29 October. No velocity dispersion was observed due to the high pre-event ambient intensities that mask the onset of this electron event (see Figure 1). PADs with a much stronger bidirectional character, nearly symmetrical around 90° pitch angle, start to be detected at the time of the electron enhancement. Bidirectional PADs with variable anisotropy magnitudes (Figures 2a–2d) were observed until 0855 UT on 30 October, coinciding with a change in magnetic field orientation (second dashed line in Figure 2). From that time, the electron PADs switched to isotropic (Figure 2e).

[15] The electron intensity-time profile evolved almost continuously following the exit from the ICME; however, ion intensities increased from 0855 UT on 30 October to a maximum near the passage of the shock S2. The bottom panels of Figure 2 (labeled I to V) show representative 1.9–4.8 MeV ion PAD snapshots as observed by the eight sectors of the LEMS120 telescope. The numbers I to V correspond to the times indicated in the first panel from the top of the time-intensity ion plot in the left-hand side of the figure. Owing to limited solar wind directional data throughout this period, the ion PADs have not been corrected for the Compton-Getting effect. However, assuming that the solar wind was predominantly radial and taking into account both the spin axis of the ACE spacecraft and the orientation of the LEMS120 telescope, the correction for the Compton-Getting effect is the same for all eight sectors. Therefore the ion PADs shown in Figure 2 are good approximations of the ion PADs that would be observed in the solar wind frame of reference. Bidirectional ∼MeV ion flows were observed inside the first ICME until 0855 UT on 30 October (second vertical dashed line in Figure 2) when both ion intensities started to increase and antisunward weakly unidirectional flows started to be observed (panel V in Figure 2).

[14] Ion intensities kept increasing up to a maximum near the passage of the shock S2, when ion PADs changed from antisunward to sunward. By contrast, electron intensities kept decreasing across the shock S2 without any significant change in their isotropic PADs. On the basis of (1) the increase in the ion intensities, (2) the change in the electron and ion PADs, and (3) the discontinuity observed in the magnetic field orientation, we suggest that the trailing edge of the first ICME crossed ACE at 0855 UT on 30 October.

[15] Kuwabara et al. [2004] used cosmic ray and magnetic field observations to derive the three-dimensional geometry of this ICME. The period of cosmic ray depleted intensity that best fits their model extended only 6 hours from 1300 UT to 1900 UT on 29 October. The fitting of a magnetic flux rope (MFR) model to the magnetic field observations used the time interval from ∼1130 UT on 29 October to ∼0200 UT on 30 October (see their Figure 4). Whereas the conclusions above from our analysis agree with the leading edge determined by Kuwabara et al. [2004] using their MFR model, their trailing edge cannot explain the bidirectional PADs observed for the time interval between c and d (or III and IV) in Figure 2, unless they are produced by reflection in the enhanced magnetic field region lying downstream of shock S1 (see discussion below).

3.2. Second ICME, 31 October to 2 November 2003

[16] Figure 3 shows, in a format similar to Figure 2, energetic ion, near-relativistic electron, solar wind, and magnetic field observations by the EPAM, SWEPAM, and MAG experiments during the passage of the second ICME convected over the spacecraft. The time interval identified by Skoug et al. [2004] as the second ICME is indicated by the black horizontal bar in the top panel. Although Table 2 of Skoug et al. [2004] indicates that the boundary of this ICME moved past ACE at 1800 UT on 2 November, we note that different solar wind signatures suggest different stop times. On the basis of the cessation of countstreaming in the suprathermal electron data and the solar wind proton temperature recovery (signatures that are most frequently present in ICMEs [see Skoug et al., 2004, Figure 3]), the trailing boundary of the ICME was observed by ACE at approximately ∼0400 UT on 2 November. The alpha particle-to-proton (α/p) density ratio, however, suggests that the trailing edge of the ICME was not observed until ∼1800 UT on 2 November [Skoug et al., 2004].

[17] After the shock S2 crossed the spacecraft (solid vertical line in Figure 3), the energetic electron intensities started decaying faster (see also Figure 2). The observation of this abrupt change in the electron decay rate coincided with the sheath region of enhanced magnetic field between the CME-driven shock S2 and this second ICME. The entry into the ICME was characterized by an abrupt decrease in ion intensities, a decrease in electron intensities, and a change of the decay rate of the electron and ion intensities (Figure 3). A slower particle intensity decay rate compared to that observed outside the ICME was established (see also Figure 1).

[18] In Figure 4, the time evolution of the angular distributions of the energetic electron and ion intensities observed by ACE in the vicinity and during the passage of the second ICME is presented. The times of the PAD snapshots shown in Figure 4 are indicated with arrows in Figure 3. Noteworthy is the fact that the electron PADs differ dramatically outside and within this ICME, consistent with our previous studies of near-relativistic electron observations during the passage of ICMEs [e.g., Malandraki et al., 2001, 2003]. In this case, isotropic PADs were observed before the entry into the ICME (Figures 4a and 4b) and abruptly switched to strongly bidirectional inside (beginning with Figure 4c), persistently observed till 2150 UT on 1 November. Bidirectional ∼MeV ion flows were observed from 0300 UT on 31 October to ∼0200 UT on 1 November (panels I–III in Figure 4). After snapshot III the magnetic field direction was such that the LEMS120 telescope
Figure 4. The 64–112 keV electron and 1.9–4.8 MeV ion pitch-angle distributions measured by the LEFS60, LEFS150, and LEMS120 telescopes of the EPAM instrument [Gold et al., 1998] at different times during the passage (and in the vicinity) of the second ICME.
sampled only a limited range of pitch angles and therefore we cannot conclude whether bidirectional ~MeV ion flows were observed. Later in the event, isotropic ion PADs were observed from 1300 UT on 1 November till ~1300 UT on 2 November when a new ion SEP event with strong antisunward unidirectional PADs was observed. No other periods of bidirectional PADs of either electrons or ions were observed throughout the rest of the time interval considered in Figure 3.

[19] Superposed upon the decay phase of the electron event a prompt solar electron event was detected with onset at ~2310 UT on 1 November. The event had a rapid onset, exhibiting a rise-time to maximum of a few tens of minutes and a long smooth decay (see also Figure 1). This event exhibited very beam-like PADs (snapshot 1 Nov/2325–2340, in Figure 4k). This is an impulsive electron event in which particles accelerated in association with a magnetically well-connected solar flare (Table 1) arrived promptly at the spacecraft [Lin, 1970, 1974]. At the time of the onset of the event, the magnetic field polarity was inward (Figure 3), and therefore pitch angles of 180° indicate particles propagating along the field line in the antisunward direction. Note the strong peak in the electron PADs for the pitch angle 180° indicating the presence of an electron beam flowing away from the Sun. The unidirectional electron PADs evolved to isotropic distributions in ~2.5 hours that persisted until the observation of strong unidirectional antisunward anisotropies during the subsequent new SEP electron events on 2 November.

[20] Our identification of the leading edge of the second ICME (at 0200 UT on 31 October, first dashed vertical line in Figure 3) is based upon the decrease in ion intensities, the change in the decay rate of electron intensities, and the start of the period with bidirectional PADs (Figure 4c). This time coincides with the start time of the ICME identified by Skoug et al. [2004]. However, the different solar wind signatures used to determine the passage of the ICME and the bidirectional energetic particle signatures detected within the ICME provide a variety of times for the trailing edge of this ICME. We argue that the ICME trailing edge passed over the spacecraft at 2150 UT on 1 November (second dashed vertical line in Figure 3), i.e., ~1.5 hours before the onset of the new prompt SEP event (Figure 4k), when the ACE/EPAM bidirectional electron flows ceased to be observed, close to the time when the magnetic field orientation changed from a smooth low-variance evolution to an oscillating changing orientation.

[21] Considering the time interval provided by Skoug et al. [2004] for the passage of the ICME (i.e., Δt = 64 hours), and taking an average solar wind speed of 750 km s⁻¹, we obtain a radial width for this ICME of ~1.2 AU. This radial width is at the high end of the distribution of radial widths reported from observations at 1 AU [Liu et al., 2005]. The two largest ICME radial widths reported from observations at 1 AU from October 1995 to October 2002 were 1.19 AU in April 2001 and 1.14 AU in September 2000 [Liu et al., 2005] which most probably involved a combination of the passage of multiple ICMEs (see the characteristics of these two ICME structures in Table 1 of Cane and Richardson [2003]). Therefore we suggest that either this second ICME at the end of October 2003 and early November 2003 was composed of different structures (supported by the discontinuity in magnetic field orientation and magnitude at 0030 UT on 1 November; see Figure 3) or its trailing edge crossed ACE before the time provided by Skoug et al. [2004] (a situation that would be supported by the different times when solar wind, energetic particle, and magnetic field signatures ceased). However, given the unusual nature of the October/November 2003 events, perhaps the large width inferred is not unreasonable, but it would remain to explain why the different solar wind and energetic particle signatures ceased at different times. Considering our estimates of the ICME boundaries, it takes 43.8 hours for the ICME to move past ACE that, assuming an average solar wind speed of 750 km s⁻¹, corresponds to a radial width of ~0.8 AU.

4. Discussion

[22] The prompt detection of an SEP event within the first ICME (29–30 October 2003) implies that the field lines threading through this structure are still rooted at the Sun, allowing direct access of solar electrons to the interior of the ICME.

[23] The bidirectional anisotropies within this first ICME are signatures of strong trapping of the observed energetic particle population. Two possible magnetic field topologies are consistent with this set of observations. Assuming the ICME is an open structure, when ACE is inside the ICME it may establish magnetic connection directly with the downstream region of the shock S1 (now beyond the observer) and also connect to the shock S2 that is beginning to propagate away from the Sun. The enhanced magnetic field region behind the shock S1, reaching ~68 nT in intensity (solid triangle in fourth panel from the top of Figure 2) moved past ACE from ~0600 UT to 1100 UT on 29 October and traveled radially away from the Sun with a solar wind speed of ~1900 km s⁻¹. At the time of the X10 flare at ~2037 UT on 29 October when new energetic electrons were injected from the Sun, this compressed magnetic field region was located at a ~0.6 AU radial distance upstream from ACE. In such an open magnetic field configuration, energetic electrons streaming in an antisunward direction can magnetically mirror at this magnetic constriction in space, reverse direction, and propagate in the sunward direction. Subsequent reflection by the increasing magnetic field close to the Sun or by the following shock S2 resulted in an efficient confinement of particles and hence the bidirectional particle flows. However, we do not know whether the increase in the magnetic field magnitude behind the shock S1 at ~1.6 AU was still strong enough to mirror these near-relativistic electrons.

[24] In order to estimate the earliest arrival time of the electrons injected at the time of the X10 flare at 2037 UT on 29 October and the formation of bidirectional electron PADs observed by ACE, we can assume that the IMF from the Sun to the downstream region of the shock S1 was radial and that particles propagated scatter-free with a pitch angle cosine close to 1. The lower limit deduced with these assumptions gives an arrival time for the 53–103 keV electrons at 1 AU at ~2054 UT on 29 October assuming that they were injected at the Sun at ~2037 UT. After mirroring, the electrons would be expected to be observed at
ACE ~2113 UT on 29 October, consistent with the observations. Similar scenarios were discussed by Malandraki et al. [2002].

[25] Another configuration consistent with the observations that provides efficient particle confinement and the formation of bidirectional flows is a closed loop magnetic field topology. When the observer is inside the ICME there is no direct connection between the observer and the shock S1 or its downstream region (beyond the observer). Energetic ion intensities at the leading edge of the ICME would be depressed with respect to those measured at the time of the shock. The observed strong bidirectional PADS in this scenario could result from the injection of electrons at both legs of looped field lines by the 29 October solar event. Particles may remain trapped within this configuration by reflection and reacceleration at the shock S2 or by reflection at the increasing magnetic field close to the Sun, bouncing back and forth between the legs of the looped magnetic field lines. Very early in the event, an asymmetry in bidirectional flows (or even a unidirectional flow) might be expected, but if present, this was most likely masked by the high particle intensities existing prior to the onset of this event.

[26] In both of the above magnetic field configurations assumed for the first ICME, solar particles that were accelerated at the time of the X10 flare were injected onto magnetic field lines both inside and outside the first ICME. The evolution of the particle intensity within the ICME was determined by the balance between the injection of particles into the ICME and the loss of particles transmitted through the boundaries of the ICME. The intensity histories observed within and around the passage of the ICME were determined by the mechanisms of particle propagation and injection onto those field lines inside and outside the ICME. Presumably, the shock S2 was able to accelerate particles as it propagated away from the Sun. The efficiency of the shock as a particle accelerator depends on the energy of the particles and the dynamic evolution of the shock [Lario et al., 1998]. The peak of the ~MeV ion intensities near the passage of the shock S2 by 1 AU, with changes in the ion PADS, suggests that S2 was still able to accelerate ~MeV ions at its arrival at 1 AU. However, the shock S2 at 1 AU did not produce a significant local electron intensity enhancement nor a change in the electron PADS. The smoothly decaying electron intensities after the peak of the SEP event at the beginning of 30 October inside the first ICME provide evidence that the sources of electrons diminished in intensity and particle loss processes started prevailing. Under the assumption of a closed field configuration, the increase in the ion intensities after the passage of the trailing edge of the first ICME at 0855 UT on 30 October (with changes in the ion PADS from bidirectional to antisunward) suggests that ACE exited from a looped field closed structure where shock-accelerated ions were mirroring and entered into the upstream region of the shock S2 where shock-accelerated ions dominated the particle population. Under the assumption of an open field configuration, the change in ion intensities and in both ion and electron PADS can only be explained if after 0855 UT on 30 October ACE disconnected from the downstream region of shock S1 and only ions coming from S2 and electrons in the decay phase of the SEP event were observed.

[27] The observation of bidirectional PADS within the second ICME also supports the presence of an interplanetary structure able to confine energetic particles propagating between reflecting points. Assuming an open magnetic structure, it is not definite whether the enhanced turbulent magnetic field formed downstream of the S2 shock is efficient enough to reflect ions and electrons propagating between the Sun and this enhanced field region. A configuration consisting of looped field lines rooted at the Sun is consistent with the existence of bidirectional PADS within the ICME, as well as the decrease in the ion intensity observed at the entry of ACE into the ICME. A halt of the observation of ACE/EPAM bidirectional PADS ~1.5 hours before the occurrence of the highly anisotropic electron event late on 1 November, along with the increase in magnetic field fluctuations, most likely denote the passage of the ICME trailing edge over ACE. No clear recovery of particle intensities was observed at the exit from the ICME. On the contrary, new SEP events (Figures 1, 3, and 4) occurred after the trailing edge of this ICME.

5. Conclusions

[28] Energetic particle observations allowed us to determine the start and stop times of the two fast ICMEs that moved past the ACE spacecraft in October–November 2003. Those times differ from those determined using solar wind and magnetic field observations [Skoug et al., 2004]. The observation of bidirectional ion and near-relativistic electron flows within both ICMEs suggests efficient confinement of particles propagating between enhanced magnetic field regions able to reflect particles. We have examined whether both open and closed magnetic field configurations are consistent with the observations. We conclude that the solar wind signatures (including countstreaming suprathermal electron flows [cf. Skoug et al., 2004]) together with the characteristics of the time-intensity profiles argue in favor of closed looped field lines [see also Gosling et al., 1992; Richardson, 1997, and references therein]. The low-energy ion intensity depressions at the entry of ACE into the first ICME and the intensity increase at the exit of ACE from the first ICME, together with the onset of the electron event within this ICME, suggest a closed looped field structure for this ICME connected to the Sun at both ends. Similarly, the low-energy ion intensity depression at the entry of ACE into the second ICME, the slower intra-ICME decay intensity rate, and the presence of bidirectional ion, near-relativistic electron and suprathermal electron flows argue in favor of a closed looped magnetic field configuration.

[29] Acknowledgments. We are thankful to our Hi-SCALE team colleagues for their support and encouragement. We also thank the ACE SWEPAM and ACE MAG instrument teams and the ACE Science Center for providing the ACE data. We thank R. M. Skoug and T. H. Zurbuchen for providing ACE solar wind data collected by the SWEPAM instrument in the "search" mode during the intense events analyzed in this paper. The CME catalogue used to identify the solar origin of the SEP events is generated and maintained by NASA and the Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a...
project of international cooperation between ESA and NASA. O. E. M. acknowledges support from the State Scholarships Foundation (I. K. Y.) through a Post-Doctoral Fellowship. This paper is prepared in the frame of the PYTHAGORAS II project, granted by the Greek Ministry of Education, NASA, through the Jet Propulsion Laboratory, supported a portion of the research at both JHU/APL and at NJIT.