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Interplanetary Coronal Mass Ejections during the October/November 2003 events: *ACE*/EPAM Solar Energetic Particle observations

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Solar energetic particles are utilized as diagnostic tracers of the large-scale structure and topology of the Interplanetary Magnetic Field embedded within two Interplanetary Coronal Mass Ejections detected in late October and early November 2003 at 1 AU by the *ACE* spacecraft. Two candidate scenarios to account for the observations in terms of open and closed magnetic field configurations are examined. We also use *ACE*/EPAM observations to reassess the boundaries of the ICMEs with respect to those previously proposed.

1. Introduction

A series of intense solar flares and fast Coronal Mass Ejections (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. 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 [1]. We provide a detailed analysis of the energetic particle signatures detected at 1 AU by the EPAM (Electron, Proton and Alpha Monitor) experiment [3] (the flight spare of the *Ulysses* HI-SCALE instrument) onboard ACE during the passage of two Interplanetary Coronal Mass Ejections (ICMEs) preceded by extremely fast solar wind observed on 29 and 30 October, 2003 [2]. The ICME leading and trailing edges are also investigated in the context of energetic particle observations with respect to those previously identified [2].

2. Observations and Data Analysis

Fig. 1 (*left*) shows an overview of the 1-min averaged differential intensities of 38-315 keV electrons (e) in 4 energy channels and 1.9-4.8 MeV ions measured by the ACE/EPAM experiment from 0000 UT on 28 Oct to 1200 UT on 3 Nov, 2003. The vertical arrows indicate the time of observation of CMEs (short thick arrows, http://cdaw.gsfc.nasa.gov) and the onset of the temporally associated soft X-ray flare emission (long thin arrows, http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp). Solid vertical lines S1 and S2 indicate two shocks, which were followed by the passage of two ICMEs.

Because of the uncertainties in the SWEPAM measurements [2] energetic particle observations provide the required piece of information to determine the boundaries of the 1st ICME. We argue that the two vertical dashed lines in Fig. 1 (*right*) denote a more accurate determination of its boundaries. At the time of the 1st vertical dashed line smooth rotations of the magnetic field direction began to be observed, a change in B from high to low variance in both magnitude and direction as well as a decrease in the ~MeV ion intensity. The e fluxes were observed to rise simultaneously at all energies at 2145 UT on 29 Oct. No velocity dispersion was observed due to the high pre-event ambient intensities that mask the onset of this e event.

Pitch Angle Distributions (PADs) with a much stronger bi-directional (BD) character start to be detected at the time of the e enhancement. Bi-directional PADs with variable anisotropy magnitudes (panels a-d) were observed till 0855 UT on 30 October (2nd dashed line), when the e PADs switched to isotropic also coinciding with a change in the B orientation. Furthermore, BD ~ MeV ion flows were observed until this time (panels I-IV), when both ion intensities started to increase and antisunward weakly unidirectional flows started to be observed (panel V).

After the shock S2 crossed the spacecraft the e intensities started decaying faster (see also Fig. 1). The entry into the ICME was characterized by an abrupt decrease in ion intensities, a decrease in e intensities and a change of the decay rate of the e and ion intensities (Fig. 2). A slower particle intensity decay rate compared to that observed outside the ICME was established. Consistent with our previous studies of near-relativistic e observations during the passage of ICMEs (e.g. [4], [5]), isotropic PADs were observed before the entry into the ICME (Fig. 2, panels a, b) and abruptly switched to strongly BD inside (beginning with panel c) persistently observed till 2150 UT on 1 Nov. BD ~MeV ion flows were clearly observed till 0200 on 1 Nov (panels I-III). No other periods of BD PADs of either e or ions were observed throughout the rest of the time interval considered in Fig. 2. Based on these observations, our identification of the leading edge of this ICME agrees with [2]. However, the different signatures used by [2] indicate different times for the trailing edge of this ICME. We argue that the ICME trailing edge passed over the spacecraft at 2150 UT on 1 Nov (2nd dashed vertical line, Fig. 2), i.e. ~1.5 h before the onset of the new prompt SEP event (panel k, Fig. 2), when the EPAM BD e 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.

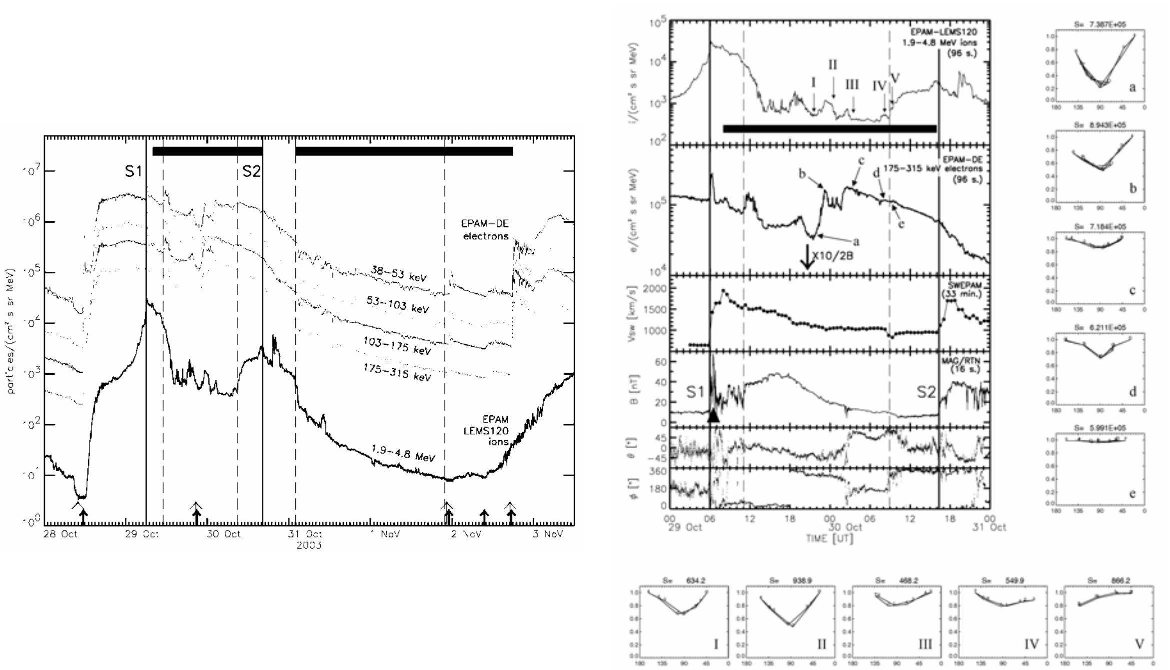

Figure 1. *left:* The black horizontal bars indicate the passage of ICMEs as identified by [2]. The dashed vertical lines indicate the passage of the ICME boundaries based upon our energetic particle observations (see text); *right:* Ion, electron, solar wind and magnetic field observations by the EPAM, SWEPAM and MAG experiments onboard ACE during the passage of the 1st ICME. 64-112 keV electron (panels a-e) and 1.9-4.8 MeV ion (panels I-V) PAD snapshots.

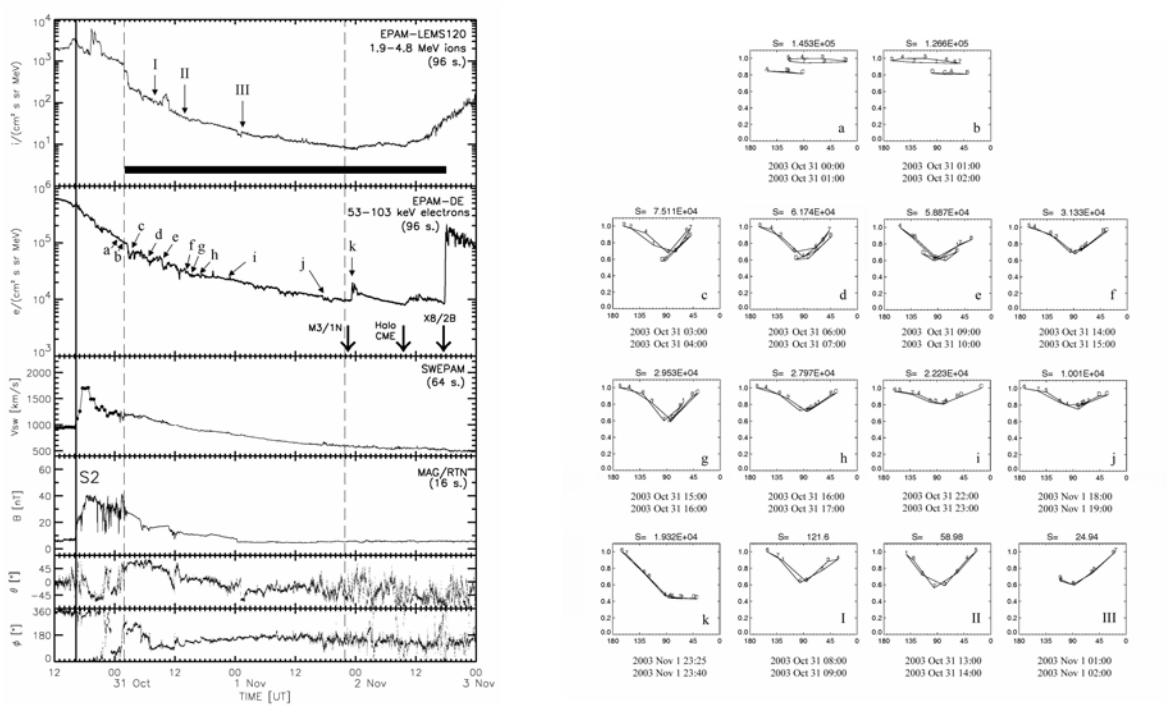

Figure 2. *left:* Ion, near-relativistic electron, solar wind and magnetic field observations by the EPAM, SWEPAM and MAG experiments onboard ACE during the passage of the 2nd ICME. The black horizontal bar indicates the time interval identified by [2] as the 2nd ICME. The dashed vertical lines indicate our identification of the ICME boundaries; *right:* 64-112 keV electron and 1.9-4.8 MeV ion PADs measured by the LEFS60 and LEFS150 telescopes of the EPAM instrument [3] at different times during the passage and in the vicinity of the 2nd ICME.

3. Discussion

The prompt detection of an SEP event within the 1st ICME implies that the field lines threading through this structure are still rooted at the Sun, allowing direct access of solar e to the interior of the ICME. 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 moved past ACE from ~0600 UT to 1100 UT on 29 Oct 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 Oct when new energetic e were injected from the Sun, this compressed B region was located at a ~0.6 AU radial distance upstream from ACE. In such an open B configuration, energetic e 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 B close to the Sun or by the following shock S2 resulted in an efficient confinement of particles and hence the BD particle flows. However, we do not know whether the increase in the B magnitude behind the shock S1 at ~1.6 AU was still strong enough to mirror these near-relativistic e. In order to estimate the earliest arrival time of the e injected at the time of the X10 flare at 2037 UT on 29 Oct and the formation of BD e PADs observed by ACE, we can assume that the IMF from the Sun to the shock S1 was radial and that particles propagated scatter-free with a pitch angle cosine close to 1. The lower limit deduced gives an arrival time for the 53-103 keV at 1

AU at ~2054 UT on 29 Oct, assuming that they were injected at the Sun at ~2037 UT. After mirroring, the e would be expected to be observed at ACE ~2113 UT on 29 Oct, consistent with the observations.

Another configuration consistent with the observations is a closed loop B topology. When the observer is inside the ICME there is no direct connection between the observer and 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 BD PADs in this scenario could result from the injection of e at both legs of looped field lines by the 29 Oct solar event. Particles may remain trapped within this configuration by reflection and re-acceleration at S2 or by reflection at the increasing B close to the Sun, bouncing back and forth between the legs of the looped B lines. Very early in the event, an asymmetry in BD 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 the event.

The observation of BD PADs within the 2nd ICME also supports the presence of an interplanetary structure able to confine energetic particles propagating between reflecting points. Assuming an open B structure, it is not definite whether the enhanced turbulent B formed downstream of S2 is efficient enough to reflect ions and e propagating between the Sun and this enhanced B region. A configuration consisting of looped B lines rooted at the Sun is consistent with the existence of BD PADs within the ICME, as well as the decrease in the ion intensity observed at the entry of ACE into the ICME.

4. Conclusions

The solar wind signatures (including counterstreaming suprathermal e flows, [2]) together with the characteristics of the time-intensity profiles argue in favor of closed looped B lines (see also [6], [7]). The low-energy ion intensity depressions at the entry into and the intensity increase at the exit from the 1st ICME, together with the onset of the e event within this ICME, suggest a closed looped field structure connected to the Sun at both ends. Similarly, the low-energy ion intensity depression at the entry of ACE into the 2nd ICME, the slower intra-ICME decay intensity rate and the presence of BD ion, near-relativistic and suprathermal e flows argue in favor of a closed looped B configuration.

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