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Solar energetic particles inside a coronal mass ejection event observed with the ACE spacecraft

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Abstract

In this work, solar flare energetic particle fluxes ($E_e \geqslant 38$ keV) observed by the EPAM experiment aboard ACE are utilized as diagnostics of the large-scale structure and topology of the interplanetary magnetic field (IMF) embedded within a well-identified interplanetary coronal mass ejection (ICME). The still controversial question of whether the detected ICME structure has been detached from the solar corona or is still magnetically anchored to it is addressed. The observation of two impulsive solar flare electron events inside the ICME suggests that field lines in this ICME are rooted at the Sun. From the time evolution of the angular distributions of the particle intensities we infer that the observations are consistent with the magnetic topology of a magnetic bottle between a magnetic mirror located at the Sun and a magnetic constriction upstream from ACE formed by the convergence of open field lines that reflects the outgoing electrons. The magnetic mirror strength is calculated in one case based upon the local IMF observations and the electron event onset characteristics. A magnetic field enhancement observed by ACE in the downstream region of the CME-driven shock is identified as the agent responsible for the mirroring of the energetic electrons. © 2002 Published by Elsevier Science Ltd.

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1. Introduction

The presence of magnetic loops anchored at the solar surface and extending out to distances beyond the Earth's orbit has been hypothesized in the past (Gold, 1959; Cocconi et al., 1958). Furthermore, it has been conjectured that magnetic loops could even be detached from the Sun to form "magnetic bubbles" (Piddington, 1958). Gosling et al. (1974), using Skylab measurements, observed 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.

Approximately, one-third of CMEs in the solar wind are also magnetic clouds (Gosling, 1990), characterized by a flux rope geometry observed as a large, smooth rotation in the magnetic field, a strong magnetic field and a low proton temperature (Burlaga et al., 1981; Burlaga, 1991; Klein and Burlaga, 1982).

The first attempt to probe the topology of interplanetary fields by means of solar energetic particles (SEPs) was made by Rao et al. (1967). They found four periods of bi-directional anisotropies of 10-MeV protons as part of a survey of energetic storm particle events observed with detectors on the Pioneer 6 and 7 spacecraft. They argued that a Gold bottle could not account for their observations which were better explained by particles behind a blast wave in

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an open field line configuration. Palmer et al. (1978), who made the next attempt to deduce magnetic field topologies from energetic particle measurements, found 16 periods of bi-directional fluxes of low-energy solar particles with an average duration of 9 h. In contrast to Rao et al. (1967) they argued in favor of a Gold bottle. Kutchko et al. (1982) analyzed a 1-MeV proton and alpha SEP event on October 12, 1977, that showed field-aligned bi-directional fluxes for about 5 h. Electron anisotropies were also bi-directional but were peaked perpendicular to the magnetic field. They compared the Gold bottle with a plasmoid as candidate topologies for the interplanetary magnetic field and the former configuration was considered to be the most consistent. Sarris and Krimigis (1982) have presented IMP-7 observations of energetic particles injected by solar flares into extended solar magnetic loop-like structures. From the development of the angular distributions of the intensities of energetic protons ($E_p \geqslant 300$ keV, $E_p \geqslant 25$ MeV) and electrons ($E_e \geqslant 220$ keV) they have inferred that energetic particles are bouncing between two magnetic mirrors located at the Sun and have obtained for the first time estimates of the extent of magnetic loops to distances ~3.5 AU from the Sun. Marsden et al. (1987) have presented the results of a comprehensive survey of low-energy ion bi-directional anisotropies and their relation to isolated interplanetary magnetic structures as observed by ISEE-3 at the time of peak activity of sunspot cycle 21. From a comparison of the anisotropy signatures at 35 and 620 keV they concluded that their observations were most consistent with the transient magnetic structures being detached bubbles consisting of closed loops or tightly wound cylindrical helices rather than extended tongue-like loops attached to the Sun at the time of observation.

Occasionally, the onset of a solar particle event is observed by a spacecraft located inside an ICME (Kahler and Reames, 1991; Farrugia et al., 1993; Mazur et al., 1998; Malandraki et al., 2000a). Such observations suggest that at least one end of the field lines embedded within the ICME is connected to the Sun, rather than detached. The onsets discussed in these studies were observed in the ecliptic within 1.5 AU from the Sun. Armstrong et al. (1994) observed hot (~270 keV) coronal particles at 4.6 AU and 32° south heliolatitude, during the passage of a CME which had an internal structure of a large magnetic flux rope. They concluded that the beams observed by the HI-SCALE instrument (Lanzerotti et al., 1992) on board Ulysses can be explained if the flux rope were rooted near a coronal energetic particle source thus providing a 'conduit' for these particles along its axis. Pick et al. (1995) have identified at 3.5 AU and 54° south heliolatitude a particle propagation channel inside an ICME which was filled by solar flare particles. These observations suggest that ICME field lines at high latitudes and large distances from the Sun may continue to be rooted at the Sun.

Gosling et al. (1995) suggested that sustained three-dimensional magnetic reconnection, occurring within the rising loops of a CME, can produce a mixture of magnetic topologies: looped magnetic field lines connected to the Sun at both ends, open field lines connected to the Sun at only one end, and disconnected field lines that are connected to the outer heliosphere at both ends. The observation of bi-directional and streaming anisotropy suprathermal electron and 0.4–5 MeV ion flux characteristics within two different portions of an ICME observed by Ulysses were interpreted by Bothmer et al. (1996) as evidence for closed magnetic loops and open magnetic field lines, respectively. Recently, Larson et al. (1997) have presented observations of five impulsive ~1–10^2 keV solar flare electron events detected while the WIND spacecraft was inside the magnetic cloud observed upstream of the Earth on October 18–20, 1995. The ~0.1–1 keV heat flux electrons and ~1–10^2 keV energetic electrons showed numerous simultaneous abrupt changes from bi-directional streaming to uni-directional streaming to complete flux dropouts. They have interpreted these as evidence that the cloud consisted of magnetic field lines connected to the Sun on both ends, on one end, and completely disconnected, intertwined together. Mazur et al. (2000) note that the mixing of the interplanetary magnetic field due to random walk may have led to the electron disconnection events that Larson et al. (1997) observed within a magnetic cloud.

Feldman et al. (1999) have studied the suprathermal electron distribution shapes within an ICME that passed over ACE on 4–5 February 1998 in order to determine its internal magnetic structure and have identified for the first time conical pitch-angle distributions (i.e. the distribution function being constant as a function of gyrophase). They suggested the conics may originate in transient electron heating associated with three-dimensional magnetic reconnection within the magnetic legs of the CMEs that generates large, complex magnetic loops. Malandraki et al. (2000b) have utilized solar flare energetic electrons ($E \geqslant 42$ keV) observed by the HI-SCALE experiment onboard Ulysses as tracers of the magnetic topology of two ICMEs detected in March 1991 at 2.5 AU. They concluded that the magnetic field structures embedded within the ICMEs were rooted at the Sun allowing direct access of solar flare electrons. Both ICMEs were found to present a filamentary structure comprising magnetic filaments with distinct electron anisotropy characteristics. The observations were consistent with portions of the ICMEs comprising both open and closed magnetic field lines.

In this work, we study the large-scale structure and topology of the IMF embedded within a well-identified ICME and the magnetic cloud contained within it based upon energetic electron observations ($E \geqslant 42$ keV) by the ACE/EPAM instrument. The question of whether the detected ICME and magnetic cloud have been detached from the solar corona or are still magnetically anchored to it when they arrive at ACE is addressed.

2. Instrumentation

In this work, hourly averaged and fine time resolution measurements of the angular distribution 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, are utilized. The LEFS60 and LEFS150 have geometrical factors equal to $\sim$0.397 cm^2 sr. The numbers 60 and 150 denote the angle that the collimator centerline of the telescope makes with the spacecraft spin axis. The EPAM experiment has been described in full detail by Gold et al. (1998). Furthermore, hourly averaged measurements of magnetically deflected electrons (DE) measured by the B detector of the CA60 telescope are also reported in the energy ranges DE1 (38–53 keV), DE2 (53–103 keV), DE3 (103–175 keV) and DE4 (175–315 keV). The CA60 has a geometrical factor of 0.103 cm^2 sr.

Fine time resolution IMF measurements are also used (see Smith et al. (1998) for a description of the ACE MAG experiment). Solar wind data were provided by the SWEPAM experiment (McComas et al., 1998) on board ACE. Information on solar activity is provided by the Solar Geophysical Data monthly report (No. 646, Part I, May 1998).

3. Observations and analysis

In Fig. 1, an overview of the hourly and spin-averaged differential intensities of four magnetically deflected electron channels (38–315 keV) as counted by the B detector head of the CA60 telescope of the EPAM experiment is presented for the interval from May 1, 1998 to 0600 UT, May 4, 1998 (from day 121 to 0600 UT on day 124). An ICME, bounded in Fig. 1 by solid vertical traces C (Commencement) and E (End), began at 0500 UT on May 2 and ended at 0100 UT on May 4. The ICME was expanding as it passed ACE. It contained a single, well-defined magnetic cloud (Osherovich and Burlaga, 1997) observed from 1300 UT, May 2 to 1200 UT, May 3 (dashed lines). (See Skoug et al. (1999) for the plasma and magnetic field parameters of this ICME.) This ICME was associated with a "halo" CME event detected at the Sun by the LASCO/C2 coronagraph onboard SOHO on April 29, 1998 (Skoug et al., 1999; Gloeckler et al., 1999). A forward shock marked by the vertical dotted line S1 in Fig. 1 was observed at 2123 UT on May 1 (Skoug et al., 1999) associated with this ICME. Furthermore, this ICME interval contains a forward shock (vertical dotted line labeled S2) observed at 1700 UT on May 3 (Skoug et al., 1999), propagating into the back of this ICME and associated with an ICME convected over ACE at a later time. No active in situ shock acceleration is evident since there are no shock-associated enhancements.

During the passage of the ICME and the magnetic cloud embedded within it two prompt electron events are clearly evident. The first one was detected after the ICME's front boundary crossed ACE, while the second one was observed after the magnetic cloud's leading edge was convected over the spacecraft, commencing after midday on May 2, 1998. Both events had a rapid onset, exhibiting the usual rise-time to maximum of a few tens of minutes, and a long smooth decay (Lin, 1970, 1974). Furthermore, these events exhibited very beam-like pitch-angle distributions. These are impulsive electron events in which particles accelerated at

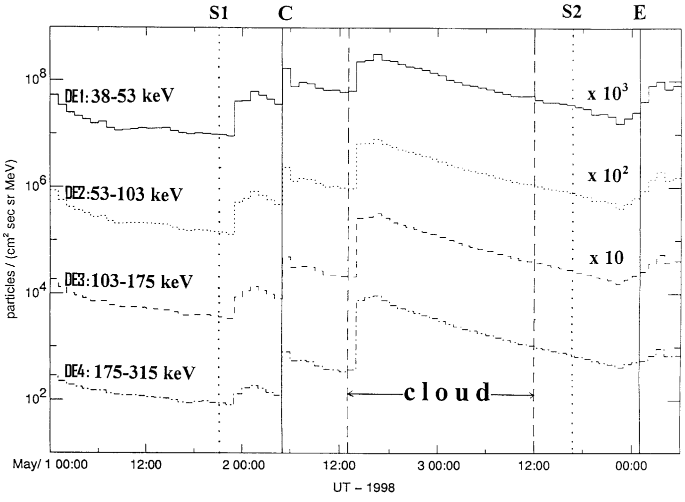

Fig. 1. Spin and hourly averaged fluxes of 38–315 keV energetic electrons versus time, observed with the ACE/EPAM instrument in the interval from May 1 to 0600 UT May 4, 1998. Solid vertical traces *C* and *E* denote the commencement and end of the ICME interval, respectively. Also depicted is the magnetic cloud structure embedded within the ICME. Dotted vertical lines S1 and S2 mark the two forward shocks observed during this period.

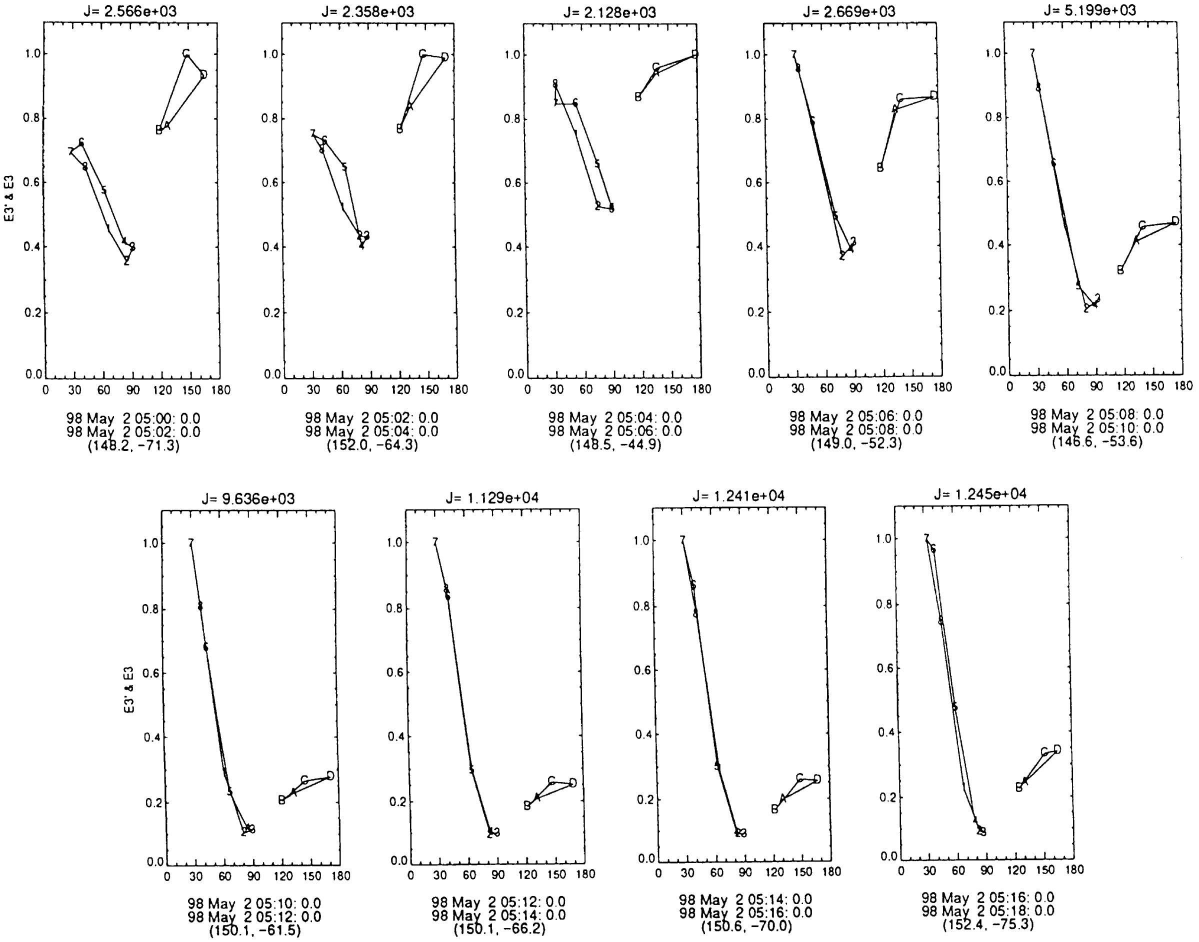

Fig. 2. Pitch angle distributions of the 112–178 keV electrons from 0500–0518 UT on May 2, 1998 are presented. Normalized differential flux is plotted versus pitch angle. Estimated instrumental backgrounds have been subtracted. The time interval is indicated below each graph; on top of the figure, J indicates the maximal flux to which the distribution is normalized.

a magnetically well-connected solar flare arrive promptly at the spacecraft (Reames, 1999).

Using the measured solar wind velocity of 650 km/s by the SWEPAM experiment on board ACE at the time of the onset of the first electron event, the length of the Parker spiral connecting ACE to the Sun, was computed to be 1.05 AU. The ACE footpoint mapped back to a longitude of W37° on the Sun as viewed from the Earth. An H-alpha importance 1B solar flare starting at 0449 UT on May 2 which was located at S12 W12 and produced by active region 8210 was reported in SGD, 1998, 646, Part I. We believe the electron event observed by ACE was initiated by this solar flare.

In Fig. 2, 2-min averaged pitch angle distributions (PADs) of the 112–178 keV electrons from 0500–0518 UT are shown. On May 2, the IMF was pointing away from the Sun. At 0506 UT, in coincidence with the observed onset of the impulsive electron event in this channel, a substantial increase in the electron fluxes streaming away from the Sun starts to be detected superposed upon the preexisting bi-directional electron fluxes. Thus, the electron population comprises an electron beam that exhibits anisotropy directed parallel to the IMF and is thus propagating away from the Sun. The particles arrive at the spacecraft from the west of the Sun. The peaked electron PADs argue for nearly scatter-free propagation of these particles during their outward transit from the solar corona to 1 AU.

In Fig. 3, the upper curve represents the maximum flux of the 112–178 keV energetic electrons streaming away from the Sun as measured in one of the eight sunward-looking sectors of the LEFS60 telescope. The lower curve refers to the flux from that sector of the antisunward-looking

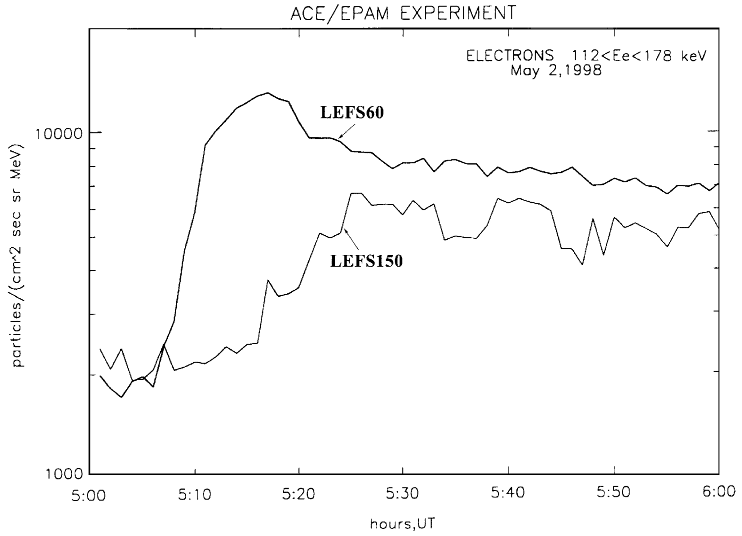

Fig. 3. Observations of energetic electrons during the onset of the first solar flare event observed on May 2, 1998. The upper curve indicates the maximum flux of electrons streaming away from the Sun, as measured in one of the sectors of the sunward-looking telescope LEFS60 for each 1 min interval. The lower curve shows the flux of the backscattered electrons.

telescope LEFS150 which is closer to the sector that is diametrically opposite to that with the maximum intensity and corresponds to electrons which are streaming back towards the Sun after having been reflected beyond ACE. Thus, the time delay between the first outgoing and the first backstreaming electrons is computed to be ~10 min which corresponds to a large-angle scattering distance beyond ACE's position of ~0.23 AU. This time delay is short compared to ~1 hour which is the time required by energetic electrons to bounce between two mirrors of a magnetic loop-like structure anchored at the Sun. The observations are rather consistent with the open field line configuration of a magnetic bottle between a magnetic mirror at the Sun and a magnetic constriction at a distance of ~0.23 AU upstream from the spacecraft formed by the convergence of open field lines which backscatters the outgoing electrons.

In Fig. 4, we present 30-s averages of the maximum flux of the 42–290 keV energetic electrons streaming away from the Sun as measured in one of the eight sunward looking sectors of the LEFS60 telescope. Background (pre-event) values have been subtracted from the intensities for all energy channels. Energetic electrons are initially streaming away from the Sun as expected for the onsets of prompt solar flare electron events (Sarris et al., 1983; Malandraki et al., 1997). Fig. 5a shows 7-min averaged PADs for the 112–290 keV electrons at 1357 UT on May 2, 1998. On that day, the IMF was pointing towards the Sun. Electrons are streaming in a collimated beam along magnetic field lines embedded within the magnetic cloud. Note the strong peak in the electron PADs for the pitch angle 180°; this is the principal signature of the electron beam. The footpoint of the 1.06 AU-long Parker spiral (for a 575 km/s solar wind velocity as measured by SWEPAM) connecting ACE to the Sun was found to be located at ~W43° as viewed from the Earth. We have associated the electron event with a great 3B/X1.1 solar flare reported in SGD, starting at 1331 UT on May 2, located at S15 W15 and produced by active region 8210. There is clear indication for a velocity dispersion in this event. Taking the FWHM of the electron beam PADs at 1357 UT on May 2 (Fig. 5a), we obtain a value of 40° as the pitch angle of this electron population. The transit times for 40° pitch angle along the spiral-arm to ACE for the mean energies of the channels are 16, 18, 22, 27 min for $E'4$–$E'1$, respectively. Thus, a delay of about 2 min should have been observed between the rises of $E'4$ and $E'3$, 4 min between $E'3$ and $E'2$ and 5 min between $E'2$ and $E'1$. Our observations are phenomenologically consistent with the expected time delays between the rises of the channels. Arrows in Fig. 4, indicate the anticipated arrival times at the spacecraft of the energetic electrons (for the mean energies of the channels) if we assume that they were simultaneously injected at all energies at 1331 UT at the Sun and propagated with a 40° pitch angle along field lines out to 1 AU. Solid horizontal bars indicate the anticipated onset times for the electrons of all energies for each energy channel. There is qualitative agreement between the anticipated onset times and the observed onset times of the event.

As it is seen in Fig. 5b, bi-directional 178–290 keV electron flows developed at 1410 UT on May 2, 1998 indicating electrons streaming towards the Sun are then detected. The time delay between the first outgoing electrons and an

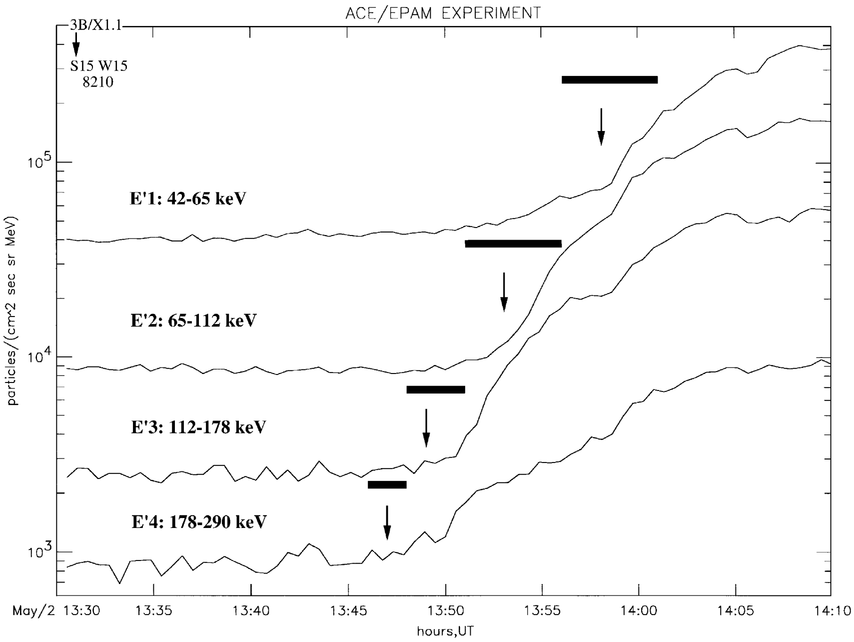

Fig. 4. Thirty seconds averages of the maximum flux of the 42–290 keV solar electron event population detected after the magnetic cloud's leading edge was convected over the spacecraft as measured in one of the eight sunward-looking sectors of the LEFS60 telescope. Arrows indicate the anticipated onset times at ACE assuming the electron beam was injected at 1331 UT at the Sun and propagated with a pitch angle of 40° to the spacecraft (see text).

electron cluster streaming back towards the Sun was ~22 min which corresponds to a ~0.72 AU distance along the IMF traversed by the energetic electrons between the spacecraft and the magnetic mirror off which they were reflected. We deduce that the observations are inconsistent with the configuration of closed magnetic loops rooted at the Sun at both ends but are better accounted for by the topology of a magnetic bottle originating at the Sun with a magnetic constriction in space.

We next estimate the mirror magnetic field strength, $B_{\rm m}$ for this event. Using the equation $B_{\rm m} = B_{\rm l}/\sin^2\theta_{\rm l}$, with $B_{\rm l} = 12\,{\rm nT}$, we find $B_{\rm m} = 29\,{\rm nT}$. $B_{\rm l}$ is the magnetic field magnitude at the spacecraft at the time of the electron event onset and $\theta_{\rm l} = 40°$, the local pitch angle at the spacecraft of the electron population observed. In Fig. 6, the magnetic field magnitude is shown from May 1 to 3, 1998. The arrow corresponds to the time of the electron event onset at the spacecraft. An enhanced magnetic field region lying downstream from the CME-driven shock and travelling radially away from the Sun with a solar wind velocity of 600 km/s passes ACE near the end of May 1. At the time of the observation of the electron event onset at the spacecraft, i.e. ~1350 UT on May 2, this compressed magnetic field region was located at a ~0.2 AU radial distance upstream from ACE. As calculated, solar flare electrons travelling along the Parker spiral magnetic field have been reflected at a magnetic mirror 29 nT strong located ~0.72 AU upstream from ACE. We believe the post-shock magnetic field enhancement that encompassed fields ~30 nT strong is responsible for the mirroring of the energetic electrons.

In Fig. 7, a detailed sketch of the IMF configuration is shown based upon the ACE observations during this period. Based upon the geometrical considerations presented we argue that reflection of the electrons detected during the impulsive event within the magnetic cloud occurred ~70° eastward from the ACE spacecaft.

4. Summary and conclusions

We have shown evidence which argues in favor of connection to the Sun of the May 2–4, 1998 ICME and magnetic cloud contained within it observed by ACE. The evidence consists of the intensity and directional distribution of energetic particles observed during the traversal of these structures over the spacecraft. If we assume that SEPs are injected into interplanetary space from the Sun while a plasmoid (i.e. a closed magnetically isolated field structure) is in space, those

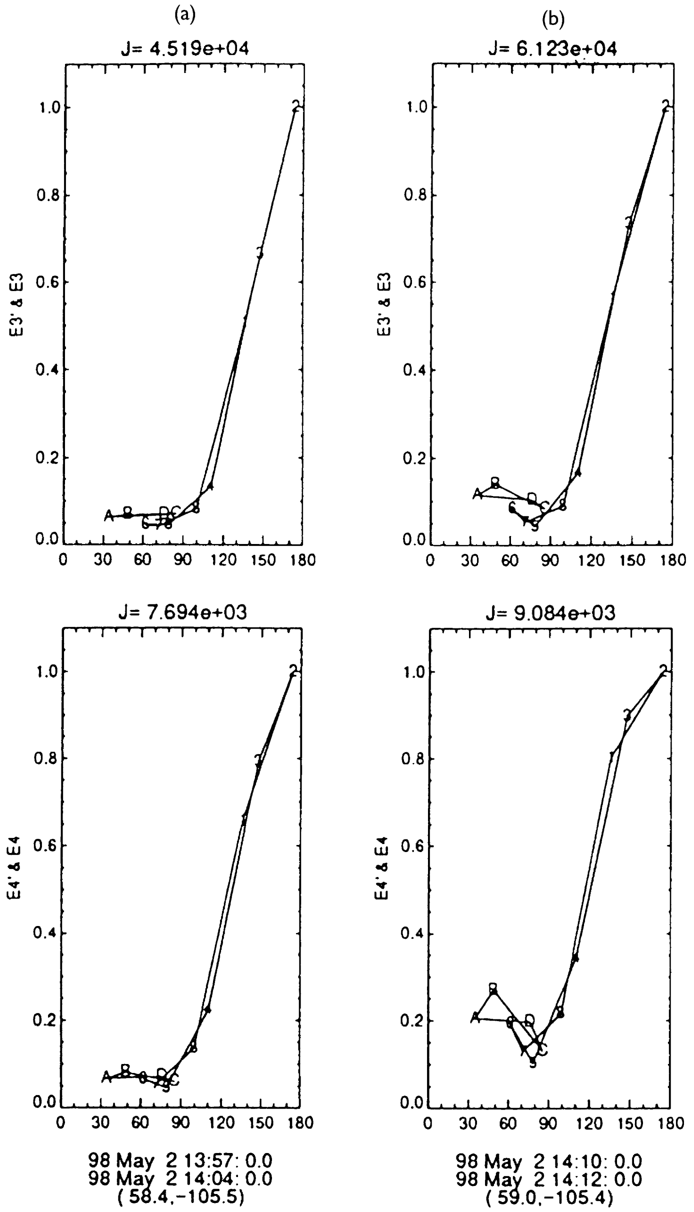

Fig. 5. (a) Seven minutes averaged PADs of 112–290 keV electrons at 1357 UT, May 2, 1998 exhibit a strong anisotropy directed antiparallel to the IMF. (b) The return 178–290 keV electron flux begins to appear 22 min after the onset of the event.

particles should be excluded from the region of the plasmoid as they would have to propagate mainly across magnetic field lines to enter it. Thus, such disconnected regions past ACE should be accompanied by substantial reductions in SEP fluxes, in contrast to what is observed. The observation of two impulsive solar flare electron event onsets within this ICME and magnetic cloud implies that the field lines embedded in these structures remained connected to the Sun allowing direct access of solar flare electrons. Therefore, we conclude that the magnetic field structures embedded within the May 2–4, 1998 ICME and its embedded magnetic cloud were still anchored at the Sun when they arrived at ACE.

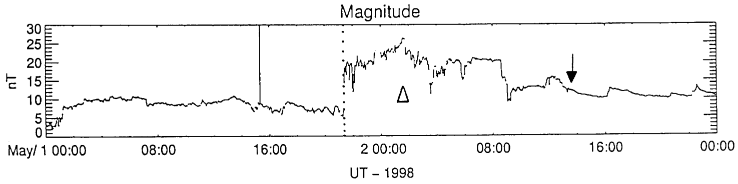

Fig. 6. Fine time resolution measurements of the magnetic field magnitude as measured by the ACE MAG experiment for the interval 1–3 May, 1998. The arrow corresponds to the time of the onset at the spacecraft of the electron event observed within the magnetic cloud. The light symbol (Δ) denotes the post-shock magnetic field enhancement ~30 nT strong considered to be responsible for the observation of the electron return flux (see text).

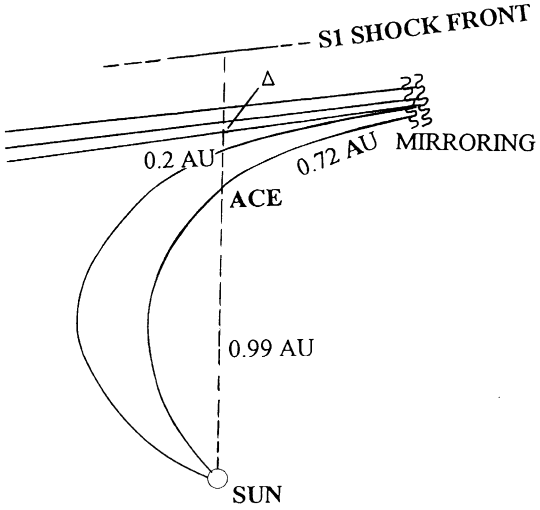

Fig. 7. Schematic of possible IMF configuration at the time of the impulsive solar flare electron event detected within the magnetic cloud on May 2, 1998.

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