TRACING THE MAGNETIC TOPOLOGY OF CORONAL MASS EJECTION EVENTS BY *ULYSSES*/HI-SCALE ENERGETIC PARTICLE OBSERVATIONS IN AND OUT OF THE ECLIPTIC

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Abstract. In January 2000, the *Ulysses* spacecraft observed an ICME event at 43° S heliographic latitude and $\sim$ 4.1 AU. We use electron ($E_e > 38$ keV) observations to trace the topology of the IMF embedded within the ICME. The still controversial issue of whether ICMEs have been detached from the solar corona or are still magnetically anchored to it when they arrive at the spacecraft is tackled. An in ecliptic ICME event is also presented.

1. Introduction

First estimates of the spatial extent of magnetic loops to distances $\sim$ 3.5 AU from the Sun were obtained by Sarris and Krimigis (1982). The observations of Armstrong *et al.* (1994) and Pick *et al.* (1995) suggested that Interplanetary Coronal Mass Ejection (ICME) field lines at high heliolatitudes and large heliodistances may continue to be rooted at the Sun. Malandraki *et al.* (2000) presented *Ulysses* observations of both open and closed interplanetary magnetic field (IMF) topologies within two ICMEs that probably resulted from 3-D magnetic reconnection at the Sun (Gosling *et al.*, 1995). In this paper, we use solar energetic particle (SEP) fluxes as diagnostics to probe the topology of the IMF embedded within two well-identified ICMEs measured by *Ulysses* at 43° S heliolatitude and in the ecliptic plane. We present measurements of the angular distributions of the intensities of interplanetary electrons in 4 energy channels (38–315 keV), as are measured by the WART B detector of the HI-SCALE instrument (Lanzerotti *et al.*, 1992).

2. Observations and Data Analysis

An overview of the hourly and spin-averaged differential intensities of electrons in two energy channels is presented from 16–22 January, 2000, in Figure 1. A solar electron event is observed. An ICME, began at 10:30 UT on January 18 and ended

Space Science Reviews **97:** 263–268, 2001.

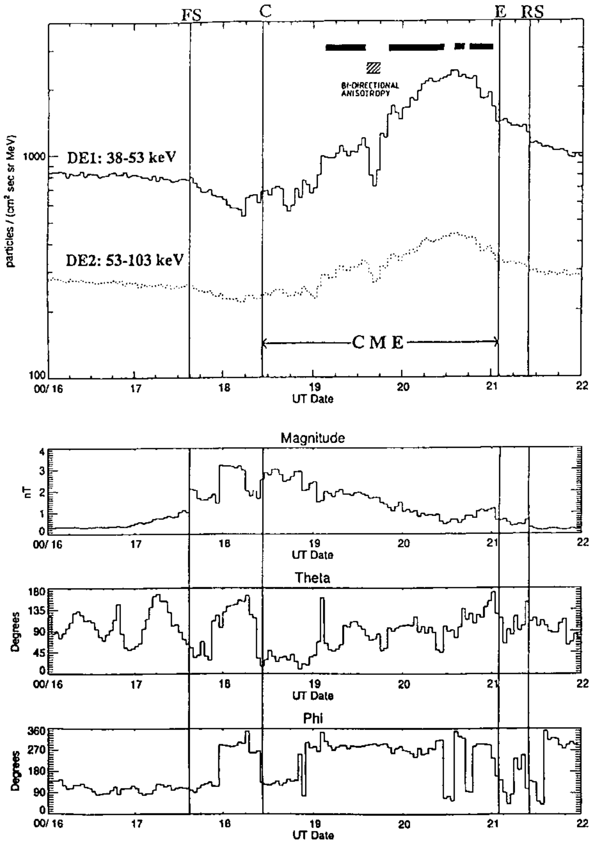

Figure 1. Ulysses energetic electron and magnetic field data from 16–22 January, 2000. Vertical traces C and E denote the Commencement and End of the ICME, respectively.

at 02:00 UT on January 21 (Gosling and Forsyth, 2001). Forward (FS) and reverse (RS) shocks were also observed (shock list at http://swoops.lanl.gov). The FS and RS strength B_d/B_u (ratio of the magnitudes of the downstream and upstream magnetic field vectors) is 2.1 and 2.3, respectively. No active in situ shock acceleration is evident in the electron fluxes since there are no shock-associated enhancements. Figure 1 also shows IMF parameters in the heliocentric RTN system. At this time, *Ulysses* was located at 43° S, at 4.1 AU helioradius and ∼48° west of the Earth. Using the solar wind velocity of 400 km s^{-1} measured by the SWOOPS experiment on January 19, the Parker spiral magnetic field line connecting *Ulysses* to the Sun, was computed to be 7.84 AU long. The *Ulysses* nominal magnetic connection longitude was at E60 on the visible hemisphere of the Sun.

A distinct enhancement is observed at all energies >38 keV at ∼01:05 UT on January 19. Since the transit time for a 38–53 keV electron with a 0° pitch-angle along the spiral is 2.5 hr, an initial injection time at the Sun at 22:35 UT on January 18 would be implied. There were no significant Hα or X-ray solar flares reported in

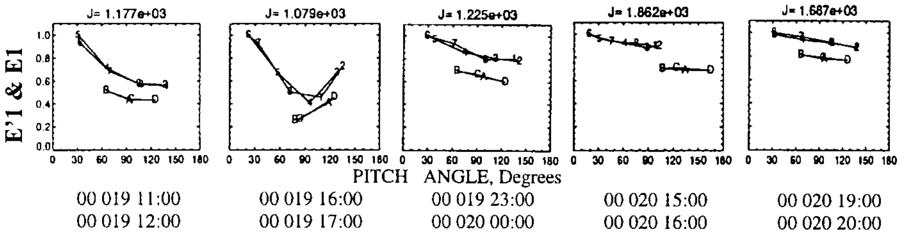

Figure 2. Time evolution of the angular distributions of the energetic electron intensities observed by *Ulysses* within the high latitude ICME (see text).

Solar Geophysical Data (*SGD*, 2000). However, numerous interplanetary Type III (TIII) radio bursts were captured by the WIND/WAVES instrument around the anticipated injection time and during January 19. The $\sim$14 MHz high frequency of the bursts corresponds to a generation location of a few solar radii. Most of these bursts were also well-associated with metric TIII bursts reported in SGD. The event has a 1.5 day risetime to maximum. The slow risetime of the event, the absence of a velocity dispersion, and the non-impulsive nature of the rising phase indicate that the electrons detected after their injection must have undergone drifts across the highly inhomogeneous magnetic fields near the Sun before reaching the *Ulysses* footpoint and escaping in space, populating this high latitude ICME.

The pitch angle distributions (PADs) reveal that after the onset of the event, *Ulysses* enters a region where strong unidirectional flow is observed (Figure 2; 1st snapshot). The anisotropy is directed parallel to the IMF, indicating the detected electrons comprise an electron beam streaming away from the Sun. Unidirectional PADs persist till 15:00 UT on January 19 (horizontal solid bars in Figure 1) when PADs dramatically change from unidirectional to strongly bidirectional (BD; hatched horizontal bar in Figure 1, 2nd snapshot in Figure 2). This transition coincides with an abrupt decrease observed in the flux profile of the event. *Ulysses* remained in this region for 3 hr and upon exiting the fluxes recovered their values. After a 2-hr interval of isotropy, the spacecraft encounters a regime where electrons are again streaming antisunward for 15 hr (3rd snapshot). During this interval the intensities are still increasing and nearly reach maximum intensity. PAD snapshots are also shown for the regions observed near the rear boundary of the ICME with electrons streaming away from the Sun for 2 and 6 hr, respectively. The ratio of forward to back anisotropy near the onset of the event was 1.8 and decreased with time to 1.25 during maximum intensity and to 1.1 during the decay phase of the event.

In Figure 3, electron fluxes are presented from 20–25 April, 1998 (*Ulysses* lagged Earth in longitude by 53° at a 5.4 AU helioradius and 6.5° S heliolatitude). An ICME extending from 08:00 UT on April 22 till 08:00 UT on April 23, 1998, was observed (J. Gosling, private communication) during the rising phase of a major prompt electron event. Faster electrons arrive earlier, characteristic of impulsive injection at the Sun simultaneous at all energies, followed by escape

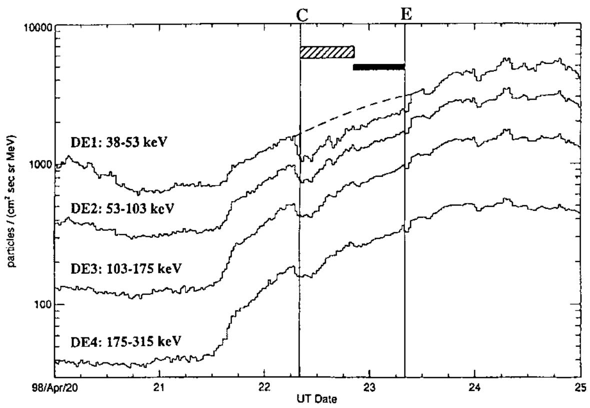

Figure 3. Thirty-min and spin-averaged electron fluxes for the interval from 20–25 April, 1998. After *Ulysses* exits the ICME electron intensities attain the values they would have had if the risephase of the event had proceeded smoothly without interruption (dashed line).

along field lines out to 5.4 AU. The electron fluxes are significantly modulated by the ICME passage as evidenced by the abrupt drop and sudden increase observed at the leading and trailing edges of the ICME, respectively. However, the electron fluxes continue to increase throughout the ICME, providing evidence that this structure is being constantly supplied during a long lasting solar electron injection. Given the spacecraft location, the Parker spiral was 16.06 AU long (calculated for a 413 km s^{-1} solar wind velocity measured at the time of the event onset) and mapped back to the east limb of the Sun. Although no flares were reported from that portion of the Sun on April 21, it is likely that the observed electrons were injected in the Sun's nonvisible hemisphere and reached the *Ulysses* footpoint after undergoing drifts across the inhomogeneous coronal λ fields. The long risetime to maximum of the event provides support for this interpretation.

The electron increases as a function of energy are shown in Figure 4. The transit times for a pitch angle of 55° (FWHM of the PADs at 02:00 UT on April 22) to *Ulysses* for the four channels are 5.38, 6.24, 7.5, and 9.24 hr. The expected delays between the energy channels are consistent with the observations within the statistics.

PADs for the event are presented in Figure 5. After the event onset and prior to the ICME there is a unidirectional flow in the electron PADs (1st snapshot in Figure 5). The IMF had a sunward direction and thus the measured electrons are streaming away from the Sun. Unidirectional PADs persist till 08:00 on April 22 when *Ulysses* enters the ICME and detects a transition from unidirectional PADs to strongly BD (hatched horizontal bar at the top of Figure 3). The region with counterstreaming electrons within the ICME lasts for 12 hr (Figure 5; 2nd snapshot). At 20:00 UT, the BD PADs switched to strongly unidirectional persistently observed for 12 hr (3rd PAD snapshot in Figure 5) until *Ulysses* exits the ICME. Strong unidirectional PADs persist to the end of April 23.

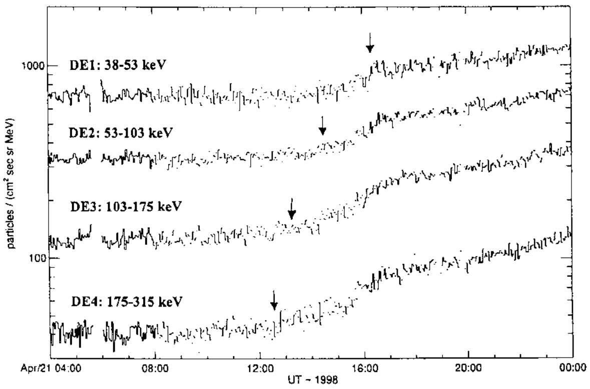

Figure 4. Onset characteristics of the electron event.

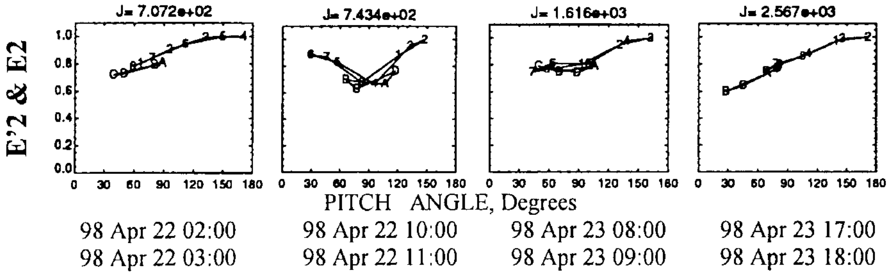

Figure 5. Hourly-averaged electron PAD snapshots outside and within the in ecliptic ICME.

3. Summary and Conclusions

We have examined the intensities and directional distributions of two solar electron events observed during the traversal of two ICMEs over *Ulysses* in and out of the ecliptic. Within the high latitude ICME we observed energetic electrons streaming for long intervals in a collimated beam along IMF lines threading through the ICME. Therefore, a large portion of the ICME most likely consisted of open IMF

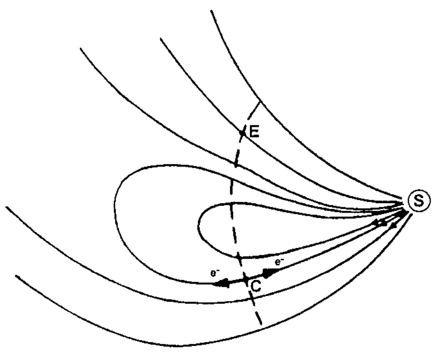

Figure 6. Sketch of closed and open IMF configuration embedded within the in ecliptic ICME.

filaments connected to the Sun at only one end that allowed the escape of electrons to 4.1 AU and 43° S. However, the 3 hr long abrupt depression observed in the flux profiles that interrupted the event risephase indicates that injected particles at the Sun could not enter this portion of the ICME. We conclude that the IMF in this portion of the ICME is most likely disconnected from the Sun. Furthermore, the observation of counterstreaming electrons throughout this region implies that the electrons are propagating within closed looped IMF lines in space. The electrons observed within this detached looped region may have been initially injected at the Sun before disconnection occurred. If electrons are injected from the Sun while a plasmoid (a closed magnetically isolated structure) is in space, these electrons would be excluded from the plasmoid since they would have to diffuse across IMF lines to enter it. Such regions moving over *Ulysses* would be accompanied by substantial reductions in electron fluxes, in agreement with what is observed.

We show evidence that solar-originating electrons have access to open field lines threading through the in ecliptic ICME. The unusual BD anisotropies observed in its leading portion are evidence for trapped electrons along closed loop-like structures anchored at both ends to the Sun. The configuration of converging open field lines that form a magnetic constriction reflecting the outgoing particles and producing the observed BD anisotropies cannot be definitely excluded. The observation of unidirectional anisotropies outside and within the ICME supports the interpretation that a large portion of the ICME and its environs most likely consisted of open IMF filaments rooted to the Sun at only one end threading through the ICME. In Figure 6, a representative schematic is shown of possible open and closed IMF configuration as evidenced by the observations of electron anisotropies. *Ulysses* proceeds along the dashed line and is thus probing IMF regimes with different flux tube configurations and anisotropy characteristics.

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