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Ulysses observations of open and closed magnetic field lines within a coronal mass ejection

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Abstract. During the rapid passage from the Sun's south to north polar regions, the Ulysses spacecraft encountered in February 1995, at 24°S, a coronal mass ejection (CME) exactly at the time when it crossed from high speed solar wind coronal hole flow into low speed streamer belt flows. We have investigated this CME, which was superimposed on an energetic particle event associated with a corotating interaction region (CIR), using energetic particle, plasma and magnetic field measurements. Ulysses' entry into the CME was accompanied by a strong decrease in the intensity of 1-3 MeV protons. The leading portion of the CME with a helical magnetic flux rope topology characteristic of magnetic clouds apparently consisted of closed magnetic loops as indicated by counterstreaming suprathermal electron fluxes along the interplanetary magnetic field (IMF) and bi-directional streaming 0.4-0.7 MeV ions. In contrast, the absence of counterstreaming electrons and ions, the presence of sunward streaming 0.4-5 MeV ions and sunward bursts of suprathermal electrons at energies from $\sim$ 40 eV up to several 100 eV inside another portion of the CME suggest that here the magnetic field lines were "open" i.e., with only one end rooted in the solar corona. These field lines were most likely connected to the reverse shock of a CIR beyond Ulysses. We suggest that 3-dimensional reconnection processes are responsible for the formation of magnetic flux rope CMEs from rising coronal loops leading to open and closed field topologies.

Key words: Sun: corona – particle emission – magnetic field – interplanetary medium

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1. Introduction

Coronal mass ejections (CMEs) are large-scale disturbances in the solar atmosphere in which large amounts of solar material are propelled outward into interplanetary space (e.g. Gosling 1993). CMEs drive shock waves ahead if they are propelled outward from the Sun with considerably higher speeds than the ambient solar wind (Gosling et al. 1976; Sheeley et al. 1985). Fast CMEs are a common cause of major large-scale energetic particle events in interplanetary space (Cane et al. 1988; Reames 1994). CMEs can also channel energetic particles out into the heliosphere over broad longitudinal and latitudinal extents through their specific magnetic topology (Bothmer et al. 1995; Bothmer et al. 1996).

Counterstreaming fluxes of suprathermal electrons (E $> \sim$ 50 eV) along the interplanetary magnetic field (IMF) are commonly thought of as the most suitable identification criterion for CMEs in the solar wind among other anomalous plasma and magnetic field signatures (Gosling 1990). It is believed that counterstreaming electrons are observed on magnetic field lines that remain rooted in the solar corona at both ends (Gosling 1990). In contrast, a field aligned heat flux of suprathermal electrons from the corona in the anti-sunward direction is present on open magnetic field lines in the solar wind that are rooted with only one end in the solar atmosphere (Rosenbauer et al. 1977). About $\sim$1/3 of all CMEs appear to have the topology of helical magnetic flux ropes as indicated by a smooth loop-like rotation of the magnetic field vector (Gosling 1993; Bothmer and Schwenn 1994,1996). These CMEs are commonly called magnetic clouds (e.g. Burlaga 1991). Gosling (1990) has suggested that the helical flux rope topology of these CMEs is likely created after a CME's liftoff from the corona as a natural consequence of 3-dimensional magnetic reconnection of rising magnetic loops. This suggestion is consistent with Soft X-ray observations of the Japanese Yohkoh satellite that showed newly formed magnetic loops in the solar corona beneath Ulysses in as-

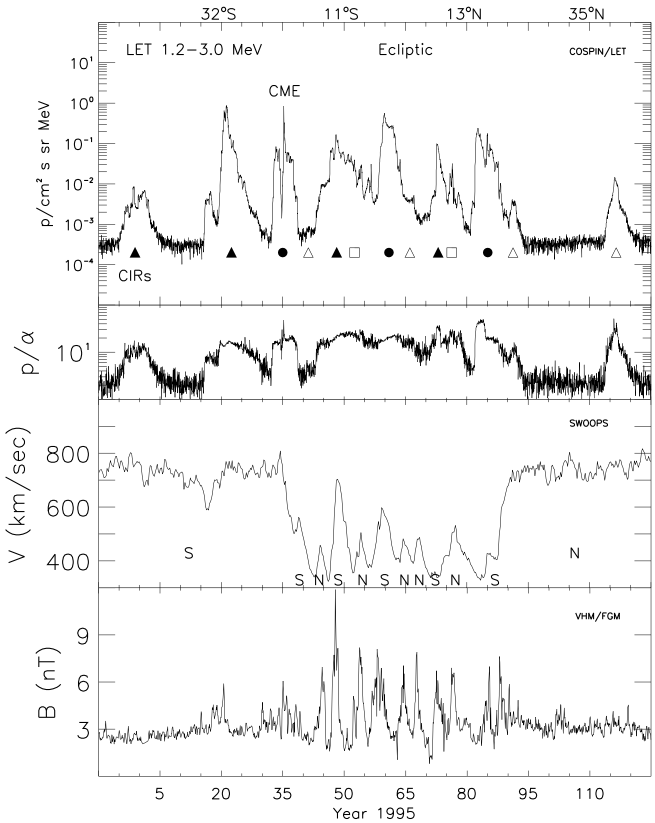

Fig. 1. Energetic particle, plasma and magnetic field data for the Ulysses fast latitude scan. Top to bottom: 1.2-3.0 MeV proton intensity, 1.0-5.0 MeV/n p/α-ratio, as detected by COSPIN-LET, solar wind speed measured by SWOOPS and magnetic field magnitude measured by the VHM/FGM magnetometer. Solid (e.g. •) and light (e.g. ∘) symbols mark particle events associated with CIRs from fast solar wind streams originating in the southern (S) and northern (N) coronal holes. A transient particle event in February 1995 which was associated with the passage of a CME over Ulysses is labelled.

sociation with a magnetic flux rope CME that passed the spacecraft (Gosling 1994).

In some CMEs counterstreaming electrons were detected not continuously but intermittently throughout the event (Gosling et al. 1995a). Gosling et al. (1995a) concluded that both closed and open magnetic field lines were embedded within these CMEs and that the open field lines found within the interior of flux rope CMEs may result from sustained 3-dimensional magnetic reconnection at the footpoints of the CMEs close to the Sun.

In addition to CMEs, another source of large-scale energetic particle events are forward-reverse shock pairs formed in corotating interaction regions (CIRs) between fast and slow solar wind streams (Barnes and Simpson 1976; Fisk and Lee 1980; Tsurutani et al. 1982; Richardson et al. 1993; Sanderson et al. 1994). Due to the steepening of the plasma and magnetic field gradients at the interface between the fast and slow streams with increasing distance from the Sun, corotating shock-pairs commonly develop at solar distances beyond ~ 2 AU (e.g. Hundhausen and Gosling 1976).

Energetic particles stream freely away from their source region along the interplanetary magnetic field (IMF), for example, from a flare site (e.g. Pick et al. 1995) or from shocks driven by CMEs (Cane et al. 1988; Bothmer et al. 1995) or CIRs (Gosling et al. 1993a; Simnett and Roelof 1995; Sanderson et al. 1995). Measurements of the flow direction of the particles can help to distinguish between sunward flowing particles accelerated in CIR-shocks further out in the heliosphere and anti-sunward flows of particles associated with fast CMEs (Marsden et al. 1987; Richardson and Cane 1993; Richardson et al. 1993). Energetic particle observations can also provide information on the possible magnetic topology of CMEs (Kahler and Reames 1991).

The orbit of the Ulysses spacecraft included a rapid passage from the Sun's south to north polar regions. The latitudinal swing across the heliosphere involved a fast crossing of the ecliptic and is commonly called the Ulysses "fast latitude scan" (Marsden and Smith 1996; Smith and Marsden 1995).

The purpose of this paper is to use low energy ion, plasma and magnetic field measurements to investigate an energetic particle/CME event detected by Ulysses at the interface between fast and slow solar wind streams during the fast latitude scan.

2. Instrumentation

This analysis is based on data from the Low Energy Telescope (LET), one of the five telescopes in the Cosmic Ray and Solar Particle Investigation (COSPIN) onboard the Ulysses spacecraft (Simpson et al. 1992). The LET instrument measures the intensity, energy spectra and elemental composition of solar energetic particles and low energy cosmic ray nuclei from hydrogen up to iron. The instrument covers an energy range from ~ 1 to ~ 75 MeV/n, using a double dE/dX vs. E solid-state detector telescope surrounded by a cylindrical plastic scintillator anticoincidence shield. The geometrical factor of the LET, defined by two circular collimators in front of the detectors, has a value of 0.58 cm^2sr for the coincidence channels. Low resolution single-detector measurements of protons and alpha particles are also made. Here, the geometrical factor is $\sim$9.1 cm^2sr.

Solar wind data were provided by the Los Alamos SWOOPS (Solar Wind Observations Over the Poles of the Sun) experiment (Bame et al. 1992) which measures 3-dimensional ion distributions over energy ranges extending from 0.257 to 35.0 keV/charge and distributions for electrons from 0.81 to 862 eV.

The Ulysses magnetic field experiment consists of a Fluxgate Magnetometer (FGM) and a Vector Helium Magnetometer (VHM) which measure the three orthogonal components of a magnetic field vector and the background magnetic field (Balogh et al. 1992). The performance of the magnetometer provides a sensitivity of $\sim$10 pT with a time resolution up to 2 vectors/second.

3. Observations

3.1. Energetic particle events during the fast latitude scan

Fig. 1 shows an overview of 1.2-3.0 MeV proton intensity, 1.0-5.0 MeV/n p/α-ratio, solar wind speed and magnetic field magnitude as observed during the fast latitude scan at solar distances between 1.3-1.6 AU. The interval shown, between December 1994 and April 1995, covers heliolatitudes between 50°S and 46°N.

The various peaks in proton intensity can be associated with CIRs identified in the Ulysses plasma and magnetic field data (see Gosling et al. 1995b; Smith et al. 1995; Sanderson et al. 1996). Particle events labelled with solid symbols (e.g. •) are associated with CIRs caused by fast solar wind streams originating in the Sun's southern (S) coronal hole, light symbols (e.g. ◦) are associated with streams from the northern (N) coronal hole. Symbols of the same kind represent intensity peaks caused by the same CIRs. Note that the CIRs were observed as separate structures in the magnetic field data whereas some of the related particle events formed merged periods of enhanced proton intensities and p/α-ratios (see the time period between day 50 and 80 in Fig. 1). The two particle events observed at high latitudes when Ulysses was completely immersed in high speed solar wind from the coronal holes had no unique CIR-signatures in the plasma and field data (1994, day 366 and 1995, day 115 in Fig. 1). Since they were observed with time-lags with respect to the identified CIRs at lower latitudes equal to the solar rotation period, we conclude that they were caused by the same interaction regions. This conclusion is based on the observation that CIRs expand with increasing distance from the Sun to higher heliospheric latitudes (Gosling et al. 1993b; Gosling et al. 1995c,d) and a possible latitudinal motion of magnetic field lines (L. Fisk, private communication) so that field lines at the position of Ulysses can be connected to the expanded CIR and its reverse shock further out in the heliosphere, allowing accelerated particles to propagate sunward along the IMF to the position of Ulysses (Simnett and Roelof 1995; Sanderson et al. 1995).

In February 1995, at 1.4 AU, 24°S, exactly at the time when the spacecraft crossed from high speed coronal hole flow to low speed streamer belt flows, Ulysses encountered a CME (Gosling et al. 1995b; Phillips et al. 1995). This was the first CME observed by Ulysses since the occurrence of CME/particle events in spring 1994 (Gosling et al. 1994a, 1994b, 1995e; Bothmer et al. 1995). The lack of transient events is typical of "quiet" periods of solar activity. It is likely that another CME passed Ulysses on 21-23 February 1995 (Gosling et al. 1995d), but without causing significant signatures in the energetic particles. No additional CME or major transient particle events were detected by Ulysses through the end of 1995 when the spacecraft had already completed its pass over the Sun's north polar regions.

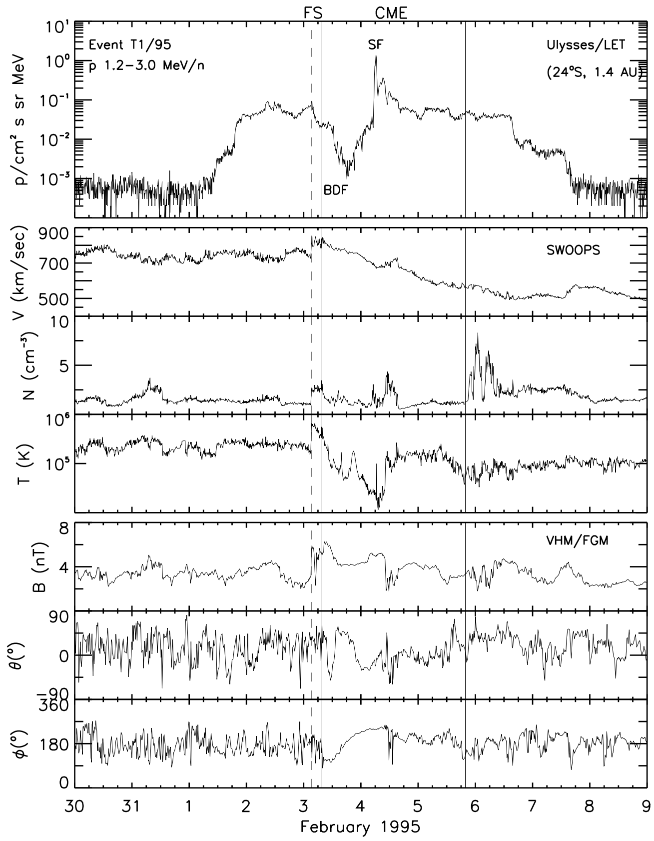

Fig. 2. Particle, plasma and magnetic field data for the energetic particle/CME event observed by Ulysses at 1.4 AU on February 3-5, 1995, at 24°S. Top panel: 10 minute averages of 1.2-3.0 MeV proton intensity, solar wind speed, density, temperature, magnetic field magnitude and latitude (θ) and longitude angles (ϕ) of the magnetic field vector in spacecraft coordinates. In this system the +Z-axis points along the spaceraft spin-axis towards the Earth, the sun-spacecraft line contains the +X-axis normal to the Z-axis and the Y-direction completes the orthogonal system. $\theta \geq 0°$ corresponds at this time approximately to a northward pointing magnetic field vector relative to the ecliptic, ϕ = 0° lies close to the Sun-spacecraft line in the plane including the spacecraft spin-axis. ϕ is measured positive in the counterclockwise direction. A field line with a magnetic polarity directed towards the Sun corresponds to ϕ-values of $\sim$135°. The forward shock driven by the CME is indicated by a dashed line, solid lines mark the interval of the CME. Periods of bi-directional (BDF) and sunward (SF) flowing particles are indicated.

3.2. The energetic particle/CME event at the interface between high and low speed solar wind

Fig. 2 presents an expanded plot of energetic particle, plasma and magnetic field data for the CME-event in early February 1995. The time-interval (7 UT February 3 - 19 UT February 5) of the CME is labelled with solid lines. Dashed lines mark a forward shock at $\sim$2 UT on February 3. The CME was identified from the plasma measurements by the anomalous low proton temperatures and low helium abundances in its leading portion and by the strong helium abundances in its trailing portion, counterstreaming suprathermal electron fluxes were observed intermittently throughout the entire interval (Gosling et al. 1995b). It is important to remark here that the choice for the back boundary of the CME is based on the helium abundances, i.e. a well established CME-signature (e.g. Gosling 1990), which was the first one observed since April 1993 when Ulysses was at a latitude of 28°S. Signatures of a helical magnetic flux rope topology (e.g. Gosling 1990; Bothmer et al. 1994) were present in the CME's leading edge between ∼7 UT on February 3 until ∼10 UT on February 4. The smooth rotation in the direction of the magnetic field is characteristic for magnetic clouds. Note that the field magnitude of this particular CME was only slightly higher than that of the surrounding solar wind. A drop in field magnitude near the center of the CME signals a change in the plasma-β, but the total internal pressure remained relatively constant. The CME showed typical signatures of an over-expanding CME in its leading portion. The forward shock appears to have been driven by the high internal pressure compared to the ambient solar wind (Gosling et al. 1995b). A reverse shock might have been detected by Ulysses if the CME's trailing portion had also been encountered inside the high speed solar wind.

The intensity-time profile of the 1.2-3.0 MeV protons shows no close correspondence with the discontinuities detected in the plasma and magnetic field data (Fig. 2). The proton intensity increased ∼2 days prior to the CME and decreased with about the same time-lag after its passage. The entire particle event is centered roughly about the CME. The minor peak in proton intensity which occurred at the forward shock was similar to what has been detected previously by Ulysses in transient energetic particle events at high latitudes (Bothmer et al. 1995). In contrast, here the leading portion of the CME was accompanied by a strong decrease in the low energy ion intensity. Such intensity decreases have commonly been observed inside CMEs in the ecliptic (Cane et al. 1988).

An outstanding feature in the energetic particle measurements is the proton intensity spike near the CME's center at ∼6 UT on February 4 which lasted until ∼18 UT. This spike occurred prior to the rise in plasma temperature, the drop in magnetic field magnitude, and the period of stronger fluctuations in the field direction. From this time on until the end of the CME the proton intensities stayed relatively constant at a level equal to that observed prior to the CME.

Fig. 3 shows the 1.2-3.0 MeV proton intensity (top panel) and the p/α-ratios (bottom panel) for the time of the CME event (solid vertical lines) superimposed upon measurements obtained one solar rotation (25.4 days) later (dotted trace) when Ulysses observed a CIR-related particle event associated with a solar wind stream from the southern coronal hole. During this period Ulysses moved from 24°S to 7°S at 1.4-1.3 AU. For better comparison of the intensity-time profiles of the energetic particles, the later data have been plotted with a reduction factor of 10^{-1}. The similarity of the intensity profiles is striking. This comparison suggests that the energetic particle event associated with the CME occurred on top of a CIR related particle population. The particles most likely originate from the CIR's reverse shock beyond Ulysses. We believe that the slightly shorter temporal extent of the later CIR event and its higher intensities are

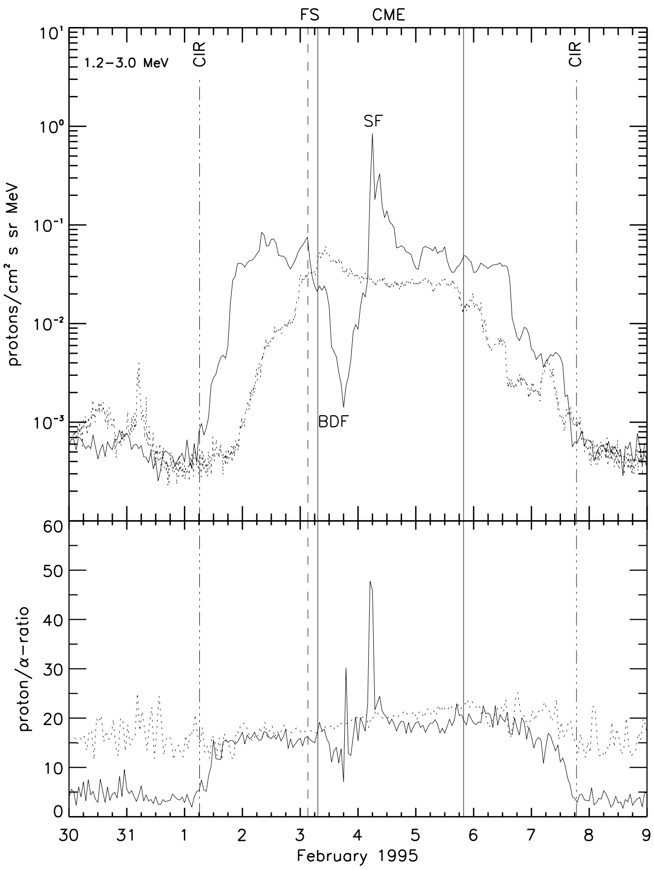

Fig. 3. Hourly averages of the 1.2-3.0 MeV proton intensity and the p/α-ratio measured by COSPIN-LET for the CME observed at 1.4 AU on February 3-5, 1995 (solid traces). Measurements obtained one solar rotation (25.4 days) later are shown as dotted traces. The proton intensity represented by the dotted trace has been plotted with a reduction factor of 10^{-1}. The CIR interval is marked and periods of bi-directional (BDF) and sunward (SF) flowing particles inside the CME are indicated.

a latitudinal effect that can be attributed to the 3-dimensional expansion of CIRs with increasing distance from the Sun as has been proposed by Pizzo (1991) and Gosling et al. (1993b). The p/α-ratios are the same in both CIR-events (bottom panel). Values in the range of 15-20 are consistent with previous spacecraft observations in the ecliptic (e.g. Kunow et al. 1991). The increase in the p/α-ratios towards the end of the event might be indicative of an increasing spatial separation of the magnetic field lines at Ulysses from the reverse shock of the distant CIR. The differences in the p/α-ratio between both events outside the CIR-interval can be attributed to the fact that the later event was observed during a period of merged CIR-particle events with increased extended p/α-ratios (see Figure 1).

Based on the observations presented in Fig. 3 the effects of the CME on the energetic particles were identified as a strong intensity decrease of the energetic protons in the leading portion of the CME associated with low p/α-ratios and a large intensity increase associated with high p/α-values near the CME's center. The CME's trailing portion showed only a minor deficit in the p/α-ratio. The first spike in the p/α-ratio occurred at $\sim$ 18 UT on February 3 in association with the initial increase of the proton intensity. The second was observed at the time of the large intensity increase of protons at $\sim$ 6 UT on February 4. At high heliolatitudes the p/α-ratios during particle events associated with CMEs were higher than those found in CIR-events (Bothmer et al. 1995, Simnett et al. 1995). It is likely that the spikes in the p/α-ratios reflect changes associated with inhomogeneities in the CME's internal plasma and field structure. As shown by the intensity-time profiles of the 1.2-3.0 MeV protons in Fig. 3, from mid February 5 the trailing portion of the CME appeared to be transparent to energetic particles from the CIR beyond Ulysses.

3.3. Evidence for open and closed magnetic field lines within the CME

Measurements of suprathermal electrons and low energy ions provided significant information on the internal structure of the CME. Counterstreaming electrons were observed on February 3 from 7 UT to $\sim$ 17 UT. We believe that this counterstreaming was associated with a closed magnetic field topology in the CME's leading portion. Our conclusion is further supported by the bi-directional field-aligned streaming of 0.4-0.7 MeV ions at $\sim$13-15 UT (S. Plunkett, private communication) as measured with the Heliosphere Instrument for Spectra, Composition and Anisotropy (HISCALE) at Low Energies (see Lanzerotti et al. 1992) and by the strong intensity decrease of 1.2-3.0 MeV protons. We have marked in Figs. 2, 3 the period of the bi-directional particle flow (BDF).

After $\sim$17 UT on February 3 counterstreaming electron and bi-directional ion flows were absent and the proton intensity and the p/α-ratio increased. At 7:30 UT near the end of the large proton intensity spike on February 4 the HISCALE measurements showed that 439-680 keV and 1.16-4.85 MeV ions were streaming towards the Sun along the IMF (S. Plunkett, private communication). The period of the sunward particle flow (SF) is indicated in Figs. 2, 3. Bursts of sunward streaming electrons at energies from $\sim$ 40 eV up to several 100 eV were observed simultaneously. Note that the sunward flowing particles were observed inside the flux-rope like portion of the CME prior to the rise in plasma temperature. We believe that the sunward flows of particles at such vastly different energies can only be explained by open magnetic field lines embedded within the CME that were magnetically connected to the reverse shock of a CIR beyond Ulysses. This conclusion is also consistent with the transparency of the CME's trailing portion to the CIR related energetic particles. The counterstreaming electron fluxes observed during the two short intervals from $\sim$6-11 UT and from $\sim$11:30-12:15 UT can be attributed to return fluxes of electrons from the CIR-shock beyond Ulysses, similar to previous counterstreaming electron events detected by Ulysses in association with CIR shocks in the outer heliosphere (Gosling et al. 1993a).

Armstrong et al. (1994) have previously interpreted a low energy particle beam inside a helical magnetic flux rope CME as indicative of open magnetic field lines. An anomaly in the radio wave activity observed at the same time also suggested a complex internal structure of this part of the CME (Stone et al. 1995). However counterstreaming electron measurements during that event suggested an open magnetic field topology in a different portion of the CME. In contrast, our observations show consistent features in both suprathermal electrons and low energy ions.

Our results show evidence for both closed and open magnetic field topologies within CMEs which are likely created by 3-dimensional reconnection of coronal loops in the rising phase of CMEs.

4. Summary

We have presented in this paper a detailed investigation of the energetic particle/CME event observed by the Ulysses spacecraft on February 3-5, 1995 at 1.4 AU, at 24°S, at the interface between high and low speed solar wind. The results obtained from low energetic particle, plasma and magnetic field measurements can be summarized as follows:

- The energetic particle/CME event was superimposed on a CIR-related particle event.
- The leading portion of the CME apparently had the structure of a helical magnetic flux rope consisting of closed magnetic field lines as supported by counterstreaming suprathermal electrons and bi-directional 439-680 keV ion fluxes along the IMF and a strong intensity decrease of 1.2-3.0 MeV protons.
- Another portion of the CME most likely consisted of open magnetic field lines that were connected to a CIR's reverse shock beyond Ulysses as supported by the lack of counterstreaming electrons, the sunward anisotropies of 0.4-5 MeV ions and the sunward bursts of suprathermal electrons.

We conclude from these findings that the topology of some magnetic flux rope CMEs is more complex than previously expected involving open and closed magnetic field topologies.

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