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The Ulysses fast latitude scan at solar maximum: COSPIN/LET energetic particle observations

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Abstract. Having completed the second survey of the southern polar regions of the heliosphere in late 2000, the *Ulysses* spacecraft is presently engaged in its second so-called Fast Latitude Scan (FSL). During this phase of the out-of-ecliptic orbit, the spacecraft makes a rapid transit from south to north, covering 160° in solar latitude in less than 320 days at relatively constant radial distance from the Sun (∼1.75 AU). In contrast to the first FSL in 1994/95 that was characterised by near-minimum solar activity conditions, the current south-to-north transit is taking place near solar maximum. Striking differences in the signatures of energetic particles are already apparent when comparing the first and second south polar passes, and it is clear that this is also the case for the two FSLs. The recurrent, CIR-related, particle increases seen in 1994/95 have been replaced by large numbers of transient events, with flux enhancements continuing up to the highest southern latitudes. In this paper, we follow the progress of the energetic particle events recorded by the COSPIN/LET experiment on board *Ulysses* as the spacecraft returns to low latitudes, and interpret the observations in the light of the associated solar activity, local plasma conditions, and the changing position of the spacecraft. We find evidence for global latitudinal transport of particles as well as rapid onset via effective magnetic connection to the source region.

1 Introduction

The *Ulysses* mission, launched in October 1990, has changed the way we view the 3-dimensional heliosphere in many fundamental ways. In particular, the investigations focusing on energetic charged particles and cosmic rays have revealed totally unexpected phenomena with respect to the global transport of these particles in the region of the heliosphere inside the orbit of Jupiter. Near solar minimum, *Ulysses* recorded the signatures of particles accelerated at low- to mid-latitude Corotating Interaction Regions (CIRs) up to the highest latitudes reached by the spacecraft (80° heliographic). At the same time, cosmic ray fluxes measured by the spacecraft at high latitudes showed recurrent depressions consistent with modulation by the same CIR structures (Balogh et al., 1999, and references therein). These observations lead to a thorough re-evaluation of the models used to describe the global configuration of the heliospheric magnetic field at the near-minimum phase of the solar activity cycle. Specifically, Fisk (1996) considered the effect of the relative motion of the differentially rotating photosphere and the rigidly rotating corona on the systematic motion of field lines in latitude, and the consequences for particle transport. In an alternative approach, Kota and Jokipii (1995) and others re-examined the importance of perpendicular diffusion. In both cases the goal was the same: to explain the unexpected ease with which energetic particles and cosmic ray nuclei were able to propagate in latitude, in a manner effectively ruled out by a standard Archimedes spiral magnetic field model (Fisk and Jokipii, 1999).

A key question to be answered in the current, solar maximum, phase of the *Ulysses* mission is: do particles have the same easy access to high latitudes when the field is much more disturbed and possesses a less well-defined global structure than at solar minimum? The observations made by the suite of particle instruments on board *Ulysses* during the recent south polar pass (September 2000 – January 2001) provided a clear answer: yes (McKibben et al., 2001). Starting in May 2000, following a period of relatively low solar activity, transient increases in particle intensity were observed at the location of Ulysses, then at high *southern* latitudes. These increases were associated with CME and/or flare activity originating predominantly in the *northern* heliohemisphere. Striking examples were events in mid-July (the so-called ”Bastille Day” event) and December (when *Ulysses* was at its maximum southern latitude).

In this paper, we follow the progress of the energetic particle events recorded by the COSPIN/LET experiment on board *Ulysses* as the spacecraft returned to low latitudes, and inter-

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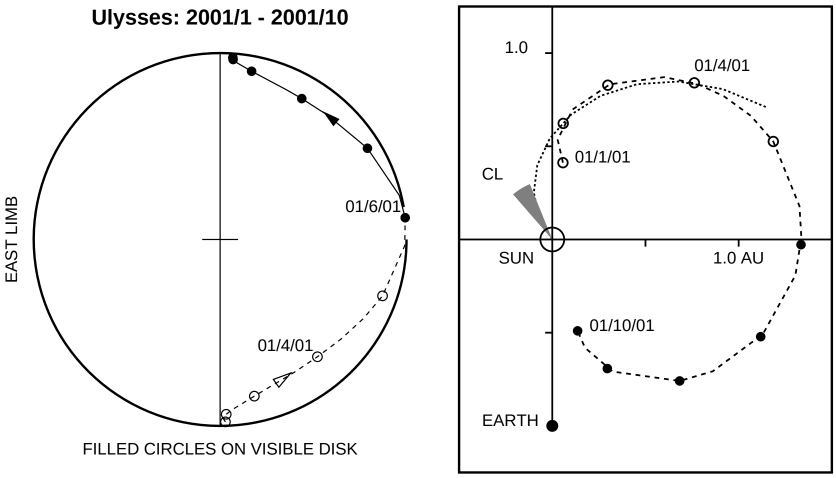

Fig. 1. The *Ulysses* Fast Latitude Scan trajectory shown in two projections (see text for details). Position markers are shown at the start of each calendar month. The segment marked CL indicates the nominal magnetic connection longitude of *Ulysses* between 1 and 20 April 2001. The dotted line shows the projection of a nominal Parker spiral field line (Vsw=400 km/s) threading the S/C on 1 April 2001.

pret the observations in the light of the associated solar activity, local plasma conditions, and the changing position of the spacecraft.

2 Observations

The observations reported here were made using the Low Energy Telescope (LET), one of the five sensors of the COSPIN experiment on board *Ulysses* (Simpson et al., 1992). The LET measures energetic nuclei in the range ∼ 1–20 MeV/n (protons), providing elemental composition information for the heavier species (Hofer et al., 2001).

Figure 1 shows the orbit of the *Ulysses* spacecraft in two complementary views. On the left, the footpoint of spacecraft has been projected onto the solar disk as seen from the Earth (in ecliptic coordinates) between January and October 2001. Open circles, plotted at the start of each calendar month, indicate a footpoint on the far side of the sun, while filled circles show footpoints on the visible (from the Earth) disk. The right-hand panel shows an ecliptic projection of the trajectory seen from the northern ecliptic pole. As can be seen, the spacecraft crossed the ecliptic heading northwards in May 2001, off the west limb of the sun as seen from Earth.

In Figure 2, we show an overview of the energetic particle fluxes recorded by the LET during the transit from the south polar regions back to the ecliptic (i.e., the first half of the so-called Fast Latitude Scan (FSL)). In the upper panel we plot the intensity of protons at two energies (∼2 MeV/n and ∼10 MeV/n) for the period 26 November 2000 (day 331) to 5 May 2001 (day 125); the lower panel shows the alpha particle intensity at approximately the same energy per nucleon. The period is seen to be bounded by episodes of relatively high particle fluxes, with numerous smaller increases in between, particularly during the first half. One point is immediately clear: energetic particles are reaching *Ulysses* in large numbers throughout its transit from pole to equator. The relative lack of enhancements seen at high energies between day 50 and 90 of 2001 is the result of lower activity at the sun during this time (*Solar Geophysical Data* (*SGD*)).

Table 1. Selected solar events in April 2001 (*SGD*).

Day/Time (Apr 2001)	Flare	AR	Comments
01/1217	M5	9415	beyond SE limb
02/1014	X1/1B	9393	N17W60
02/1136	X1	9415?	
02/2150	X20	9393	crossing W limb
03/0357	X1/1N	9415	S21E83
06/1921	X5/SF	9415	S21E31
09/1534	M7/2B	9415	S21W04
10/0526	X2/3B	9415	S23W09
11/1326	M2/1F	9415	S22W27
12/1028	X2/SF	9415	S19W43
15/1350	X14/2B	9415	S20W85

As noted above, the particle fluxes at the start of the FSL are high following enhanced solar activity in November 2000. The intensity profile subsequently shows a near-exponential decay over a period of ∼15 days. This is followed by a number of modest events in January 2001, probably associated with a series of M-class flares and halo CMEs observed at the time. The largest was an M7/2B flare on 20 January. We will not discuss this period further here, however; rather, we will focus for the remainder of the paper on the second high-flux interval, the sequence of particle events recorded at *Ulysses* during April 2001.

2.1 April 2001 energetic particle events

The first half of April 2001 was characterised by extremely high solar activity (*SGD*), including the largest flare of solar cycle 23 to date (an X20 on 2 April). The period also had the largest sunspot group of the cycle (associated with Region 9393). A second active region, Region 9415 (located at S21 and visible on the solar disk between 3 and 16 April), was also responsible for a large number of energetic X-ray flares and CMEs (see Table 1).

As can be seen from Figure 1, *Ulysses* was located in the south-west quadrant (as viewed from Earth), moving equatorward. Taking a nominal solar wind speed of 400 km/s and

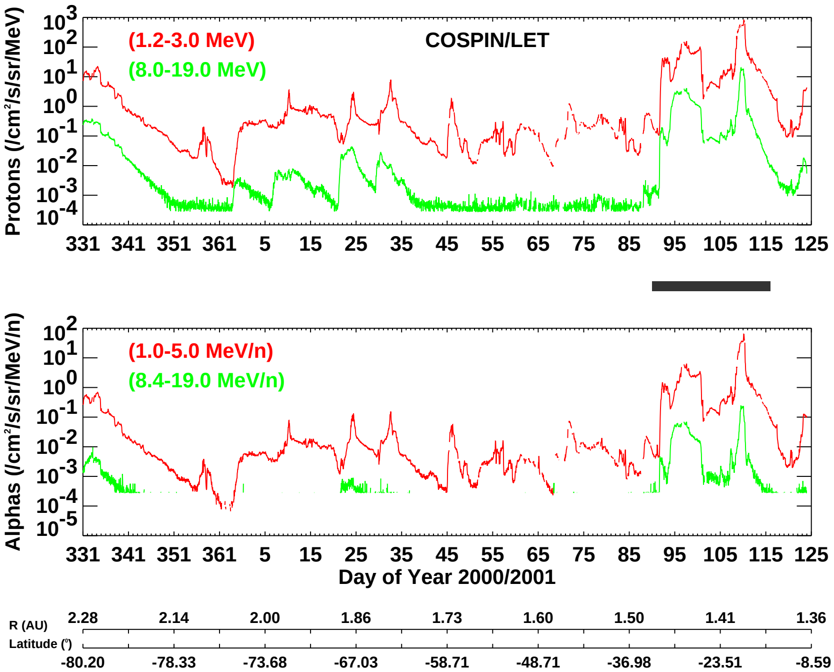

Fig. 2. Proton (upper panel) and alpha particle (lower panel) fluxes recorded by the COSPIN/LET in the energy ranges shown for the first part of the Fast Latitude Scan: 26 Nov 2000 (day 331) to 5 May 2001 (day 125). Also shown are the heliocentric radial distance R and heliographic latitude of the *Ulysses* spacecraft. The period marked with a horizontal bar is shown in more detail in Figure 3.

a simple Parker spiral field configuration gives an approximate magnetic connection longitude in the range 140°–160° East of the Sun-Earth line (marked as "CL" in the right-hand panel of Figure 1) at heliographic latitudes decreasing from 30° to 25° south. This implies that *Ulysses* is most likely to be affected by flare activity in the south-east (or beyond the east limb), and by westward-propagating CMEs, during the period in question.

Armed with this information, we will attempt to interpret the intensity profile corresponding to the last ∼30 days shown in Figure 2. The intensity increases in this period, shown in more detail in Figure 3, are some of the largest seen by the LET in the 10.5-year mission of *Ulysses* to date, only exceeded by the March 1991 events (e.g., Sanderson et al., 1992). The general enhancement begins with a sharp rise in all energy channels on 1 April 2001 (day 91), showing some evidence of velocity dispersion.

Of the possible candidates listed in Table 1, the M5 X-ray event on 1 April seems the most likely source of this increase. As noted above, AR 9415 was just beyond the east limb at this time, and its southerly location (S21) suggests a good magnetic connection to *Ulysses* at 32° south heliographic latitude. A forward shock passed the spacecraft at the time of the onset, but it is unclear if this contributed to the steepness of the onset. The flux profiles show a relatively rapid decay at the higher energies, again consistent with a well connected event. Before the fluxes have returned to background levels, however, a new event sets in. This event has a much broader profile than the first, and is probably associated with the X20 flare from AR 9393 on 2 April. Here again, there is some indication of velocity dispersion albeit less pronounced than the first increase. The low-energy particle fluxes peak around the middle of 6 April (day 96), consistent with the passage of the CME-related shock at 1312 hrs (R. J. Forsyth, private communication). If associated with the X20 flare, this would imply an average shock speed of 630 km/s.

The next major feature in the flux profiles is a sudden decrease in intensity by more than an order of magnitude at all energies occurring on 10 April (day 100). Clearly, this is a spatial rather than a temporal feature, most likely the result of a large transient disturbance passing the spacecraft (R.J. MacDowall, private communication). From Table 1, it appears that a possible candidate could be the CME associated with the X5 flare from AR 9415 on 6 April, although this originated from a point ∼30° east of central meridian. Its southerly location would, however, increase its effectivity as a barrier to energetic particles at *Ulysses*. Whatever the origin of the disturbance, the particle fluxes remain depressed for a period of ∼5 days, showing little evidence of increases directly associated with the X-class flares on 10 and 12 April. The nominal magnetic connection at this time was, however, poor. The next major solar event was an X14/2B flare on 15 April (day 105), again from AR 9415. At the time of this flare, AR 9415 was crossing the west limb, and so was well positioned with respect to the line-of-sight to *Ulysses*. The CME associated with this event passed the Earth at 0005 hours on 18 April (*SGD*), and the CME shock is responsible, we believe, for the major increase in particle intensity at *Ulysses* two days later. Following the passage of the CME shock at ∼0240 hrs on 20 April (R.J. Forsyth, private communication), the intensity drops simultaneously in all channels, presumably due to the shielding effect of the disturbance.

Summarising the observations at this time of high solar activity, we can say the following. Two active regions were responsible for major solar flares, including the largest events

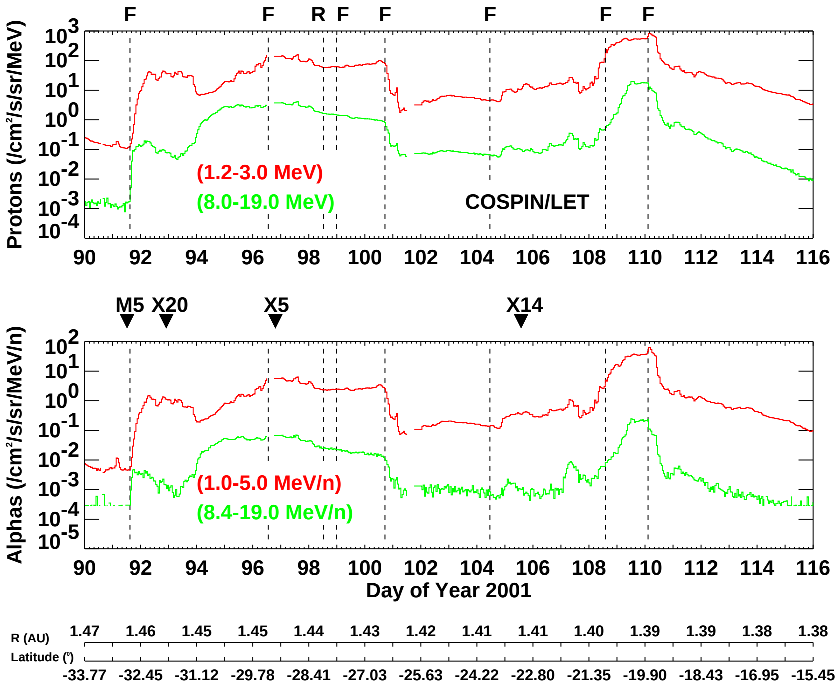

Fig. 3. As for Figure 2. for the 26-day interval beginning 31 Mar 2001 (day 90). Inverted triangles mark the time of maximum for selected flares from Table 1. Dashed vertical lines mark the times of forward (F) or reverse (R) shock passage (R.J. Forsyth, private communication).

of the current cycle: AR 9393 located at N17, and AR 9415 located at S21. *Ulysses*, at ∼1.4 AU and heliographic latitude decreasing from 32° to 14° south, recorded a variety of particle events associated with this activity, including one with rapid onset, and one more gradual event. Two sudden decreases in intensity occurred, most likely the result of the passage of transient disturbances related to CMEs.

3 Discussion and Conclusions

A key feature of the *Ulysses* southern polar pass at solar maximum has been the appearance of significant fluxes of energetic particles up to the highest latitudes, implying effective latitudinal transport over a wide range of latitudes (McKibben et al., 2001). As the spacecraft returned to low latitudes during the FSL, the appearance of a highly active region (AR 9415) in the southern helio-hemisphere (a rarity in the current cycle) created a unique opportunity to explore this phenomenon further. The particle increases in April 2001, when the spacecraft was at mid-southern latitudes, show features that we interpret as evidence for a mixed mode of propagation: in addition to the global transport of particles in latitude seen when *Ulysses* was at the highest latitudes (and largest separation from the active regions responsible for particle acceleration), the data presented here show periods when particles gain relatively easy access to the observer. We attribute this to the favourable magnetic connection offered by AR 9415 shortly before its rotation on to the east limb.

The effects of multiple CMEs and other transient disturbances propagating outward from the sun and passing *Ulysses* are clearly seen in the simultaneous decreases in intensity by more than an order of magnitude over the full range of energies covered by the LET. These Forbush decrease-like effects, which we also attribute to activity from AR 9415 as it progressed westward, are clearly more pronounced than disturbances from AR 9393 located in the northern helio-hemisphere, even though the latter produced the largest X-ray flare of the current cycle (23).

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