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Particle observations and propagation in the Three-Dimensional Heliosphere

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Abstract: Ulysses, the first spacecraft ever to fly over the poles of the Sun, plays a central role in the Heliospheric Network, the international fleet of spacecraft to explore the Sun and Heliosphere. In November 2006, Ulysses began its passage over the Sun's south pole for the third time. Although like during the first polar passes in 1994/1995 the Sun is again close to its activity minimum, an unexpected rise of solar activity occurred in December 2006. Active Region 10930 produced a series of major solar flares with the strongest one (X9.0) recorded on December 5 after it rotated into view on the solar east limb. We present energetic particle observations by Ulysses located at >70 deg south heliolatitude during this period and discuss their implications for particle propagation to solar polar regions. The observed events are also compared with previous Ulysses high latitude measurements obtained close to solar maximum. Furthermore, comparisons with data acquired from ACE – another spacecraft of the Heliospheric Network - near the ecliptic plane are discussed.

Introduction

The joint ESA/NASA Ulysses spacecraft is now in its third roughly six-year polar orbit of the Sun. Having recently completed its third survey of the southern polar regions of the heliosphere it is presently engaged in its third so-called Fast Latitude Scan (FLS). Although the Sun is again close to its activity minimum solar activity has been more prevalent during the declining phase of the current solar cycle (23rd) [e.g. *Malandraki et al.,* 2007; *McKibben et al.,* 2005] than was the case in the declining phase of the 22nd solar cycle, when the first polar passes occurred (1994/1995). In this paper, we report in and out-of-ecliptic energetic particle observations obtained by the Ulysses and ACE spacecraft during the period of intense solar activity in December 2006. Higher-energy particle observations onboard Ulysses are discussed by *Heber et al.,* 2007.

Observations and Data Analysis

After it rotated into view on the solar east limb Active Region 10930 began producing a series of X-class flares. The strongest one was an X9.0 solar flare recorded on Dec 5 at S07 E79 as viewed from the Earth. On Dec 6 it produced an X6.5 at S06 E63 and as it rotated across the solar disk an X3.4 on Dec 13 and an X1.5 on Dec 14 on the western hemisphere of the Sun. All flares were associated with particularly intense type II radio bursts which provide evidence of propagating coronal shocks at the Sun. A rare Moreton Wave – a.k.a. 'solar tsunami'- was observed to flow out of the X6.5 flare heading predominantly south (http://spaceweather.com/index.cgi).

Figure 1 shows from top to bottom energetic proton intensity profiles in four energy intervals in the energy range 1.2-19.0 MeV as measured by the Ulysses/COSPIN/LET telescope [*Simpson et al.,* 1992] as well as solar wind speed and Interplanetary Magnetic Field (IMF) magnitude observations in December 2006. The radial solar distance and the heliographic latitude of the s/c are shown at the bottom of the figure. Solid vertical lines indicate the times of passage of three Forward shocks with no associated ICME signatures detected during this period. This constitutes a unique observation by Ulysses at high latitudes. The COSPIN/LET 8-19 MeV proton channel mainly responds to galactic cosmic rays but when the level of solar activity increases it responds to solar particles. A major SEP event was observed in response to this rise of solar activity. This event was observed when Ulysses was immersed in high speed solar wind flow emanating from the southern polar coronal hole. The shocks observed are possibly related to active region 10930 and the X-class flares observed. The shocks arrive at Ulysses on days 344 (Dec 10), 345 (Dec 11) and 351 (Dec 17) so the delays are all about 5 days consistently implying shock speeds of the order of 1000 km/sec. However, what is striking is that shocks associated with low latitude events are able to reach Ulysses.

Figure 2 shows the position of *Ulysses* with respect to the fixed Sun-Earth line, projected onto the solar equatorial plane as viewed from the north (top) and on a plane perpendicular to the solar equator as viewed from the Earth toward the Sun (bottom) on Dec 5 (left) and 13 (right). The ideal Archimedes spiral magnetic field lines connecting *Ulysses* to the Sun are also shown, calculated using the measured solar wind speed at *Ulysses* on the this day. On Dec 5 there was an angular separation of 70 deg in longitude between the nominal *Ulysses* magnetic footpoint and the X9.0 flare location. This separation was ~135 deg for ACE. Obviously, as the Sun rotated Ulysses became more poorly connected while ACE became better connected to the flares.

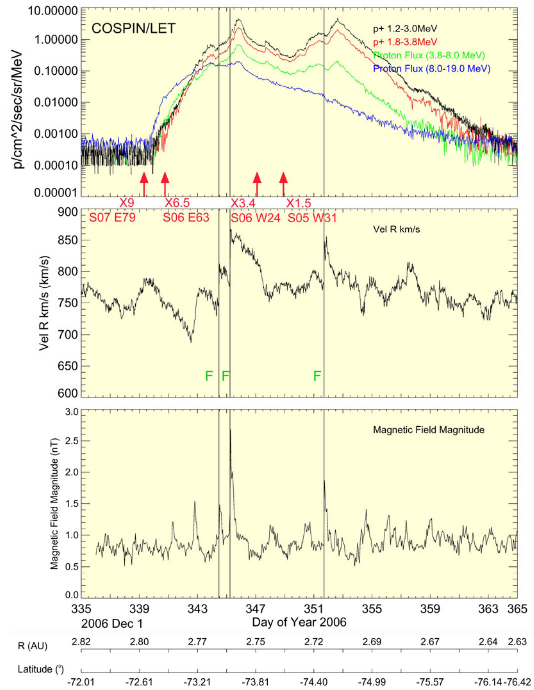

Figure 1: Overview of 0.9-19 MeV energetic proton intensities as measured by the Ulysses/COSPIN/LET, solar wind velocity and IMF magnitude in December 2006.

The onset and decay profiles of the event for 8-19 MeV protons (blue trace, Figure 1) were relatively smooth. The event has a 'clean' onset, occurring in a period nearly devoid of solar wind structures and with relatively low pre-event intensities. At Ulysses the 8-19 MeV proton intensities are observed to start increasing at 20:00 UT on Dec 5 i.e. ~10 hrs after the X9.0 flare. This time delay is longer than that expected for protons travelling along a nominal Parker spiral connection. A possible explanation lies in the time needed for the coronal shock associated with the flare to reach field lines connected to Ulysses. A slower rate in the event risephase is observed after the occurrence of the X6.5 flare in the high energy proton channel. No additional increase in the high energy proton profiles was observed in response to the Dec 13 or 14 flares. However, increases were observed in the lower energy profiles suggesting a mixture of particles due to the solar events and locally accelerated by the traveling interplanetary shocks.

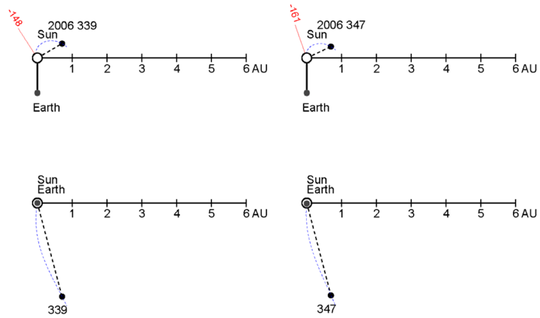

Figure 2: Position of Ulysses with respect to the fixed Sun-Earth line on Dec 5 and 13 (see text).

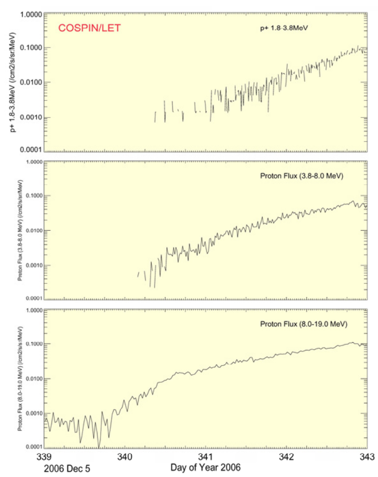

Figure 3: A clear velocity effect is observed.

A noteworthy feature not usually observed at COSPIN/LET energies up to 19 MeV at the location of Ulysses is a velocity dispersion effect detected at the onset of the event (Figure 3). This is probably due to the fact that this was an isolated event that occurred during a period of relatively quiet and stable conditions in the heliosphere. However, the time difference between the onsets at different energies was ~1 day, not consistent with expected time delays for direct propagation along a Parker spiral providing possible evidence that the particles have undergone diffusion.

Preliminary results (not shown) reveal that near-isotopic electron angular distributions are observed after the onset of the event. The magnetic field in the fast solar wind is much more turbulent than in the slow solar wind so propagation in the fast solar wind should be much more difficult leading to significant scattering of the particles. The flow directions during the rising phase of the December 2006 event were along the field and there was no evidence for any net flow across the field lines. Thus, there is no evidence of cross-field diffusion as originally suggested to explain the Ulysses observations during the Bastille Day 2000 event at high southern latitudes during solar maximum [*Zhang et al.* 2003]. Note that for the Bastille Day 2000 event a transient structure complicated the interpretation of the anisotropies observed at the onset of the event [*Sanderson*, 2004].

Observations in the December 2006 event suggest that the particles propagated to high heliographic latitudes travelling along the magnetic field lines and not across them. These features are reminiscent of the four large SEP events Ulysses observed in fast solar wind during its second northern polar pass near solar maximum [*Sanderson,* 2004; *Lario et al.*, 2004]. However, the December 2006 event that occurred during a period of relatively quiet and stable conditions in the heliosphere consists a unique observation throughout the Ulysses mission.

Figure 4 shows hourly averages of 175-315 keV electron intensities as measured by the HI-SCALE experiment [*Lanzerotti et al.,* 1992] onboard Ulysses at 72 deg south heliolatitude and ~3 AU (black trace) and by the EPAM experiment [*Gold et al.,* 1998], an identical experiment onboard ACE at 1 AU (dotted line), during the December 2006 period. The correlation between the event at ACE and Ulysses suggests that SEPs had access at both low and high latitudes.

The intensities at the two locations achieved near equality only very late in the decay phase of the particle events indicating the formation of the "reservoir effect" but only during that time interval.

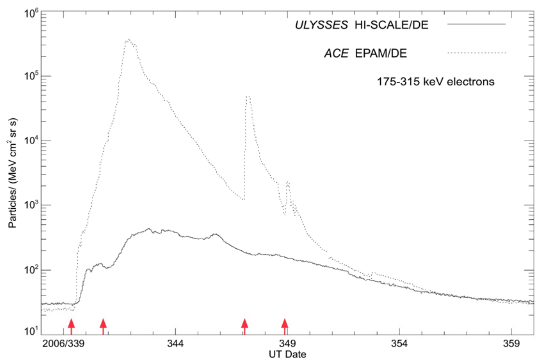

Figure 4: Comparison of hourly-averages of near-relativistic electron intensities at high latitudes with those in the ecliptic (see text).

Summary and Conclusions

We have presented a unique SEP event observed by Ulysses in December 2006 over the Sun's south pole that occurred near solar minimum with a relatively quiet and stable interplanetary structure in the heliosphere. The most likely origin of the event was the series of solar flares observed at low latitudes between 5 and 14 December. Ulysses observed a delayed onset possibly due to the time taken for the coronal shock to reach high latitude field lines connected to the spacecraft. The rise-time of the event at ACE in response to the X9.0 flare is faster than at Ulysses (although this corresponds to an eastern poorly connected event as viewed from the Earth). Thus the onset of the event seems to suggest a more diffusive transport to high latitudes than to ACE. Reservoir effects were observed only late in the events of December 2006. These effects were generally observed by Ulysses at high latitudes in the very disturbed interplanetary environment characteristic of solar maximum [e.g. *McKibben et al*. 2003].

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