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Solar Energetic Particles from the October/November 2003 Events Observed by the Ulysses COSPIN Instruments Near 5 AU

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We report observations of solar energetic particle intensities at energies from 0.8 to >100 MeV from the COSPIN energetic charged particle telescopes on *Ulysses* during series of intense solar energetic particle (SEP) events in October/November 2003. At the time, *Ulysses* was at 5.2 AU and only ~6° north of the heliographic equatorial plane and approaching Jupiter for a distant flyby. Comparison with observations at 1 AU shows that, unlike during solar maximum when particle intensities frequently approached spatial uniformity within a few days, the particle populations in the inner heliosphere were highly non-uniform throughout the events, strongly guided and confined by magnetic structures such as stream interfaces and CMEs in the solar wind. Points of particular interest are: 1) observation during onset of differential filling of flux tubes at 5.2 AU by high energy (>~20 MeV) protons; 2) apparent exclusion of SEPs from the interior of a large CME; 3) an impulsive onset of Jovian electrons observed within the closed fields of the CME.

1. Introduction

At the time of the series of intense solar events in October/November 2003, detailed observations of the solar energetic particles produced by these events were available from spacecraft near Earth (ACE, IMP-8), Jupiter (*Ulysses*), Saturn (*Cassini*), and in the far outer heliosphere (*Voyager 1,2*). These spacecraft

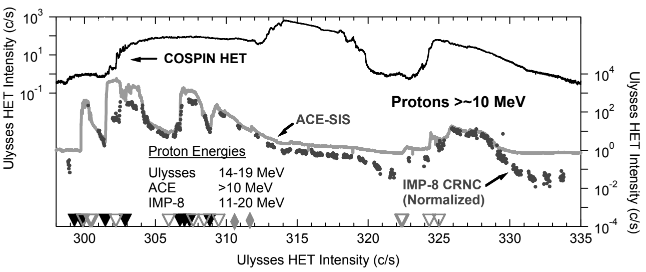

Figure 1: Observations of >10 MeV protons from *Ulysses*, near Jupiter, and ACE and IMP-8 near Earth during the period of intense solar activity in Oct/Nov. 2003. At low intensities background dominates the ACE counting rate measurements while the PHA-based IMP-8 measurements continue to give a true measure of the proton intensities. Black triangles mark X-class solar events, Open grey triangles mark M class events >M3, and the grey diamonds mark two large fast backside CMEs identified by LASCO

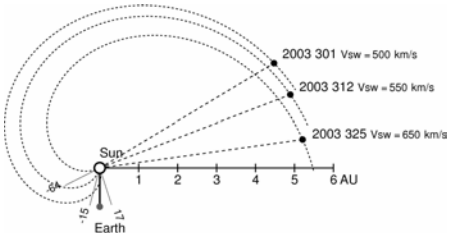

Figure 2: Ideal Parker field lines through *Ulysses* on three selected days, using the measured solar wind velocity and in a coordinate system with the Earth-Sun line held fixed. Although considerable distortions are likely during this disturbed period, Parker field lines would have connected *Ulysses* to the visible face of the Sun for almost the entire active period.

together formed a "Great Observatory" for studying the the heliospheric effects of these events as they propagated outwards. Lario et al. [1] have given a summary of theses multi-spacecraft observations. In this paper we focus on observations from the Cosmic and Solar Particle Investigations (COSPIN) energetic charged particle instruments [2] on the *Ulysses* spacecraft, discussing only a few of the highlights from the observations. McKibben et al. [3] have recently given a much more comprehensive report.

2. Observations

Figure 1 shows a comparison of observations of >~10 MeV protons from *Ulysses*, ACE [4], and IMP-8 [5]. The time-intensity profiles were so different as to seem almost unrelated. Whereas IMP and ACE record at least 8 distinct onsets during the period, *Ulysses* records only 4. At no time do the 1 AU and *Ulysses* profiles suggest approach to a uniform intensity distribution as was commonly observed in the inner heliosphere near solar maximum [6]. The events that seem to dominate at *Ulysses* are events on day 301 (X17 at S15, E08),

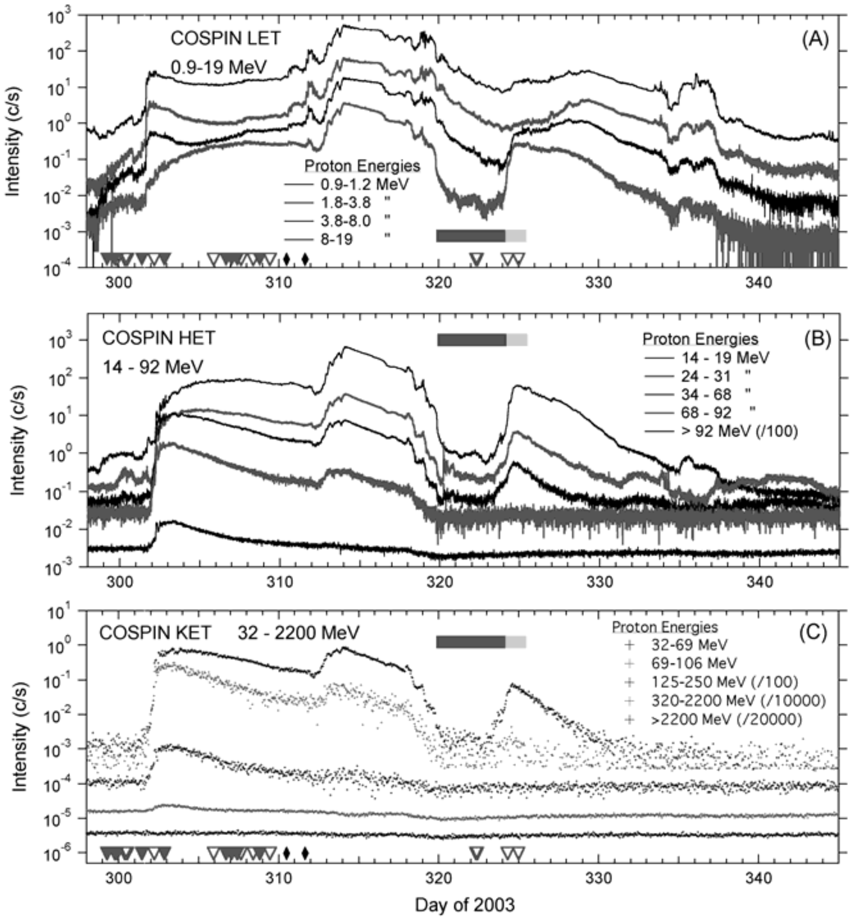

Figure 3: Overview of observations of solar protons from the COSPIN LET (A), HET (B), and KET (C). Triangle and diamond symbols have the same meaning as in Figure 1. The dark gray bar indicates the certain duration of the major CME produced by the events as identified by de Koning et al. [7]. The connected lighter gray bar indicates an ambiguous period when only some parameters were consistent with *Ulysses* being within the CME.

days 310 and/or 311 (backside CME's), and, possibly, one of several M class events on day 322 (N00, E18). More discussion of the origin of the particles is given by Lario et al. [1] and McKibben et al. [3]. As suggested by Figure 2, *Ulysses* should have been most sensitive to radially propagating disturbances, originating behind the West limb of the Sun. For particles propagating along the Parker spiral field lines, *Ulysses* was connected to the visible face of the Sun through almost the entire period of activity [3].

Figure 3 shows observations of solar energetic protons from COSPIN instruments covering an energy range from 0.9 to >2200 MeV. Accelerated protons were observed up to energies >320 MeV. The onset following the day 301 event, shown in more detail in Figure 4, was unusual in two respects. First, the onset did not show the expected velocity dispersion. In fact, the apparent onset for low energy protons occurred before their earliest possible arrival by streaming along the Parker spiral field. McKibben et al. [3] show that the onset coincides with a possible solar wind stream interface, suggesting that these particles were accelerated in an earlier event but were prevented from reaching *Ulysses* by the stream interface. The onset of low energy particles from the day 301 event was then obscured by the already enhanced fluxes. Second, a remarkable series of oscillations in the intensity (and also in the anisotropy and magnetic field direction [3]) occurred during the onset. The absence of velocity dispersion suggests that these intensity variations resulted from spatial variations convected past the spacecraft. The spatial scale, indicated by the black bar in Figure 4, was ~0.04 AU. The observations are reminiscent of the differential filling of flux tubes reported by Mazur et al. [8] for much lower energy protons following an impulsive solar particle event. However, this interpretation is difficult to maintain at the radius of *Ulysses*, and for the particle energies in question.

As shown in Figures 3 and 5, following the second major onset observed by *Ulysses*, which may have been associated with one or both of two large, fast backside CME's observed by LASCO on days 310-311, a remarkable dropout in intensity occurred at all energies, coincident with the arrival of the large, probably merged CME produced by the intense series of events starting on day 301. The intensities remained depressed, in some cases to near background levels, for the duration of the CME, which is indicated by the gray bars in the figures. The dark gray corresponds to the period when bidirectional streaming of superthermal electrons was observed [7], presumably implying closed field lines. The light gray corresponds to a following period of ambiguity, during which some CME-like characteristics were observed

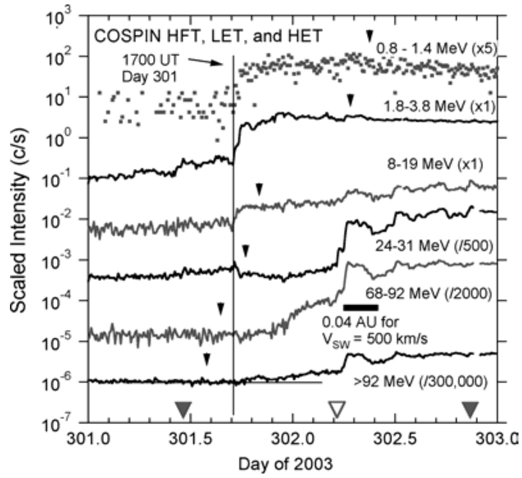

Figure 4: Onset in selected channels following the X17 event on day 301 (gray triangle). Black triangles mark the earliest possible arrival for particles streaming along a Parker field for each channel. The vertical line indicates the time of a possible stream interface.

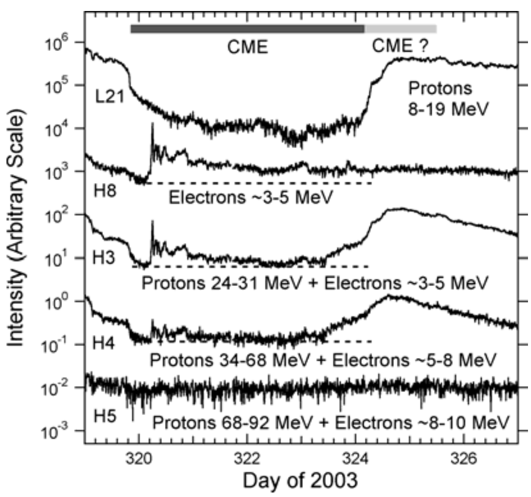

Figure 5: An electron onset, almost certainly Jovian, observed inside a large CME. The LET channel (L21) is highly immune to electrons. Other channels measure a mix of protons and electrons as shown.

in the field and solar wind. The strong intensity decrease at the onset of the CME, and the strong increase upon exiting the closed field region suggest that SEPs were excluded from the interior of the CME. The fact that at all energies the intensity increased to within a factor of about 3 of the levels expected from extension of the previous decay suggests that the new population may be partly composed of the population observed prior to the CME. However the case is not compelling, and the new particles may have been accelerated by M-class activity that occurred on day 322 while *Ulysses* was embedded in the CME. In this case, the new particles may also have been excluded from the CME, and the onset delayed until *Ulysses* exited the CME.

As shown in Figure 5, an impulsive onset of electrons, almost certainly Jovian in origin, occurred while *Ulysses* was embedded in the CME. The fluxes are highly anisotropic [3] and the event seems to be a "jet" event of the sort discovered after *Ulysses*' first flyby of Jupiter in 1992 [9]. This would imply a direct magnetic connection to Jupiter's magnetosphere. The onset time corresponds roughly to the time when the CME, considered as a spherical front, might have been expected to impact Jupiter's magnetosphere, suggesting either a triggered emission from Jupiter as a result of interaction with the CME, or establishment of a direct connection with Jupiter within the closed fields of the CME. As shown by the dashed lines, set at the pre-event level for each of the several channels, the electron intensity remained elevated for more than a day after the onset. Further study of the event is underway and may yield new information about propagation of energetic particles within a CME, both by direct propagation along the field, and, through understanding of the extended enhancement, of diffusive propagation within the closed field regions.

3. Final Remarks

We have presented a very brief and top level report of some of the remarkable features of solar energetic particles observed in association with the period intense solar activity in October/November 2003. We have given elsewhere [3] a much more extensive discussion of the intensities, of their association with interplanetary solar wind and magnetic structures, and of the particle anisotropies throughout this complex series of events. Even so, the work so far has been largely descriptive, and much further work remains to be done. For interested investigators, essentially all of the observations used in this work and in the more comprehensive report [3] are available from the *Ulysses* Data System at http://helio.estec.esa.nl/ulysses/.

4. Acknowledgements

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