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Solar Energetic Particle Events in the Rising Phase of Solar Cycle 23: Observations at 1 and 5 AU

D. Lario[1], **R.G. Marsden**[1], **T.R. Sanderson**[1], **M. Maksimovic**[1], **A. Balogh**[2], **R.J. Forsyth**[2], **S. Dalla**[2], **R.P. Lin**[3]

[1]*Space Science Department of ESA, ESTEC, Noordwijk, The Netherlands*
[2]*Imperial College of Science and Technology, London, England*
[3]*Space Sciences Laboratory, University of California, Berkeley, USA*

Abstract

We present energetic particle observations by the Ulysses and WIND spacecraft during the years 1997-1998. This period corresponds to the onset of the new solar cycle (23) when the increasing level of solar activity started to produce solar energetic proton (SEP) events. Several large and long-lasting SEP events were observed by both spacecraft during episodes of intense solar activity, even when their heliolongitudinal and heliocentric separation was large. We focus the study on the SEP events observed by WIND and Ulysses during November 1998. We suggest an interpretation of these events in terms of the activity occurring at the Sun and the heliospheric location of both spacecraft.

1 Introduction

In January 1997 the Ulysses spacecraft was at a distance of 4.71 AU from the Sun and at heliographic latitude of 19°N, moving equatorward completing its first out-of-ecliptic orbit. In April 1998 Ulysses reached its apogee at 5.41 AU from the Sun and started its second orbit enroute to the southern pole. At the end of December 1998 it was located at a distance of 5.20 AU from the Sun and at heliographic latitude of 19°S. During its journey, Ulysses made continuous observations of energetic particles. Heliospheric conditions during the period 1997-1998 changed from a very low level of solar activity in the first half of 1997 to a pre-maximum phase of the solar cycle 23 in 1998. Several large SEP events, characterized by gradual intensity time-scales, were observed by Ulysses and by other spacecraft located around the orbit of the earth. The proximity of Ulysses to the ecliptic plane during this period allows us to study the effects of the solar activity on the particle population at different heliospheric distances and heliolongitudes but at similar heliolatitudes.

Ulysses particle observations presented in this paper were made with the COSPIN/LET instrumentation (Simpson et al. 1992). We use 10 minutes averaged proton flux in the range from 1.2 to 19 MeV. We also use measurements from the Ulysses solar wind plasma experiment (Bame et al. 1992) and the magnetometer (Balogh et al. 1992). Observations close to 1 AU were done by the 3DP instrument aboard WIND (Lin et al. 1995). WIND was initially placed in a halo orbit around the Lagrangian point (L1) between the earth and the Sun. On 17 November 1998 (day 321), WIND adapted a new petal orbit around the earth which brought it to consecutive magnetospheric crossings. We use observations of energetic protons in the energy range from 400 keV to 13.5 MeV. We also use observations from the WIND magnetometer MFI instrument (Lepping et al. 1995) to identify magnetic field structures arriving at WIND.

Figure 1 shows 1-day averaged 8.0-19.0 MeV proton fluxes observed by Ulysses (thick trace) and 1-day averaged 7.9-10.7 MeV proton fluxes observed by WIND (thin trace) during 1997 and 1998. In quiet times the COSPIN/LET 8.0-19.0 MeV proton channel responds mainly to galactic cosmic rays, but during times of increased solar activity it also responds to solar particles, so it can be used as a measure of intense solar activity. Early in 1997 there are no increases observed. The first increase corresponds to the events of November 1997. Throughout 1998, there are five periods that stand out against the rest of the profile for their high proton intensity and duration. Those are the periods of April-May 1998, the two peaks during June 1998, the enhancement at the beginning of October 1998, and the long-lasting events in November 1998 and at the end of August 1998. In broad terms, there is similarity between WIND and Ulysses profiles, although closer inspection reveals that there is rarely a one-to-one correspondence. Detailed analysis for some of these periods have already been done (see for example Lario et al. (1998) for the November 1997 events or Marsden et al. (1999) for the April-May 1998 events). Here, we discuss the particle events in November 1998, which present the peculiarity that, in principle, WIND and Ulysses were located within the same magnetic flux tube. That allows us to analyze how fluxes evolve as they propagate out to 5 AU, and suggest the factors responsible for the different flux profiles at 1 and 5 AU.

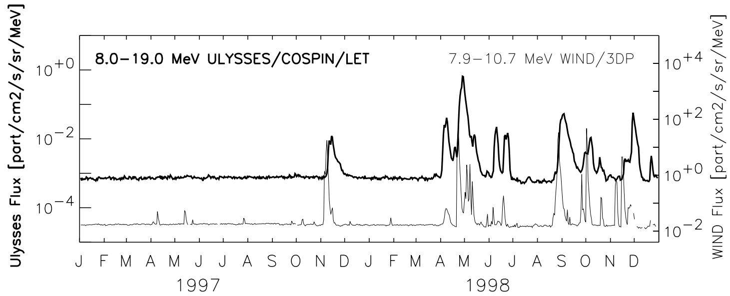

Figure 1: 1-day averages of 8.0-19.0 MeV proton intensities as measured with Ulysses/COSPIN/LET (thick line) and of 7.9-10.7 MeV proton intensities as measured with WIND/3DP (thin line). Right [left] axis applies for WIND [Ulysses] observations.

2 The particle events of November 1998

The left panels of Figure 2 show WIND and Ulysses observations from day 309 to day 344. Small arrows in the upper part of each panel indicate the CMEs and solar flares occurring during this period as pointed out by Boulder Preliminary Reports (http://www.sec.noaa.gov/weekly.html) and LASCO CMEs lists (ftp://lasco6.nascom.nasa.gov/pub/lasco/status/). A detailed list of these solar events is given in Table 1. Association between CMEs and flares is only based on their temporal occurrence and the observed CME direction of propagation.

WIND particle data allow us to discern three particle flux enhancements during this period. The first was observed between days 310 and 315 and was associated with the halo CME at 309/2044 UT. Previously to this CME another halo CME occurred at 308/0418 UT. Two interplanetary shocks were observed by WIND at 311/$\sim$0800 UT and at 312/$\sim$0400 UT. The first shock was probably associated with the CME at 308/0418 UT (average transit shock speed of $\sim$540 km s^{-1}) but it did not show a specific contribution to the proton flux which was already dominated by the protons coming from the second CME. The second shock was followed $\sim$15 hours later by a magnetic cloud, and probably was associated with the halo CME at 309/2044 UT (average transit shock speed of $\sim$740 km s^{-1}). This shock contributed clearly to the proton flux at all energies which had a local maximum around the time of the shock passage. The subsequent solar events in Table 1 did not contribute to SEP events at WIND, with the exception of the solar flare at 318/0508 UT (whose parent active region was about two days behind the west limb of the Sun) which we associate with the long-lasting SEP event observed by WIND from day 317 to 325. This SEP event was observed just after WIND crossed the earth's magnetosphere (indicated by shading bars in the top panel of Figure 2). A new series of solar events occurred in the period between days 326 and 332. AR 8384 was very active when crossing the west limb of the Sun and produced several X-ray flares. Data gaps from the WIND spacecraft do not allow us to discern the actual effect of these solar events on the proton fluxes.

The right panels of Figure 2 show two snapshots of the spatial configuration of the Sun, Ulysses and WIND on day 312 (top) and day 330 (bottom). Two nominal IMF lines connecting WIND and Ulysses to the Sun have been plotted using a solar wind speed of 400 km s^{-1}. The top panel sketches the two interplanetary shocks associated with the CMEs at 308/0418 UT and at 309/2044 UT. As can be seen, Ulysses and WIND were located within the same flux tube. In principle, those SEP events observed by WIND, after propagation effects, ought to be observed later by Ulysses. However, Ulysses detected only a small particle enhancement at low ($<$8 MeV) energies between days 312 and 317. We associate this particle event with the CME at 309/2044 UT whose shock produced a large SEP event at WIND. This particle event was less intense at Ulysses than at WIND. Several factors may be the responsible for this observation: (1) The high background level at low-energy fluxes observed during this period (and due to previous particle events) prevents us to see the real onset of this SEP event at Ulysses. (2) Assuming a radial shock propagation, there is a moment when the shock dri-

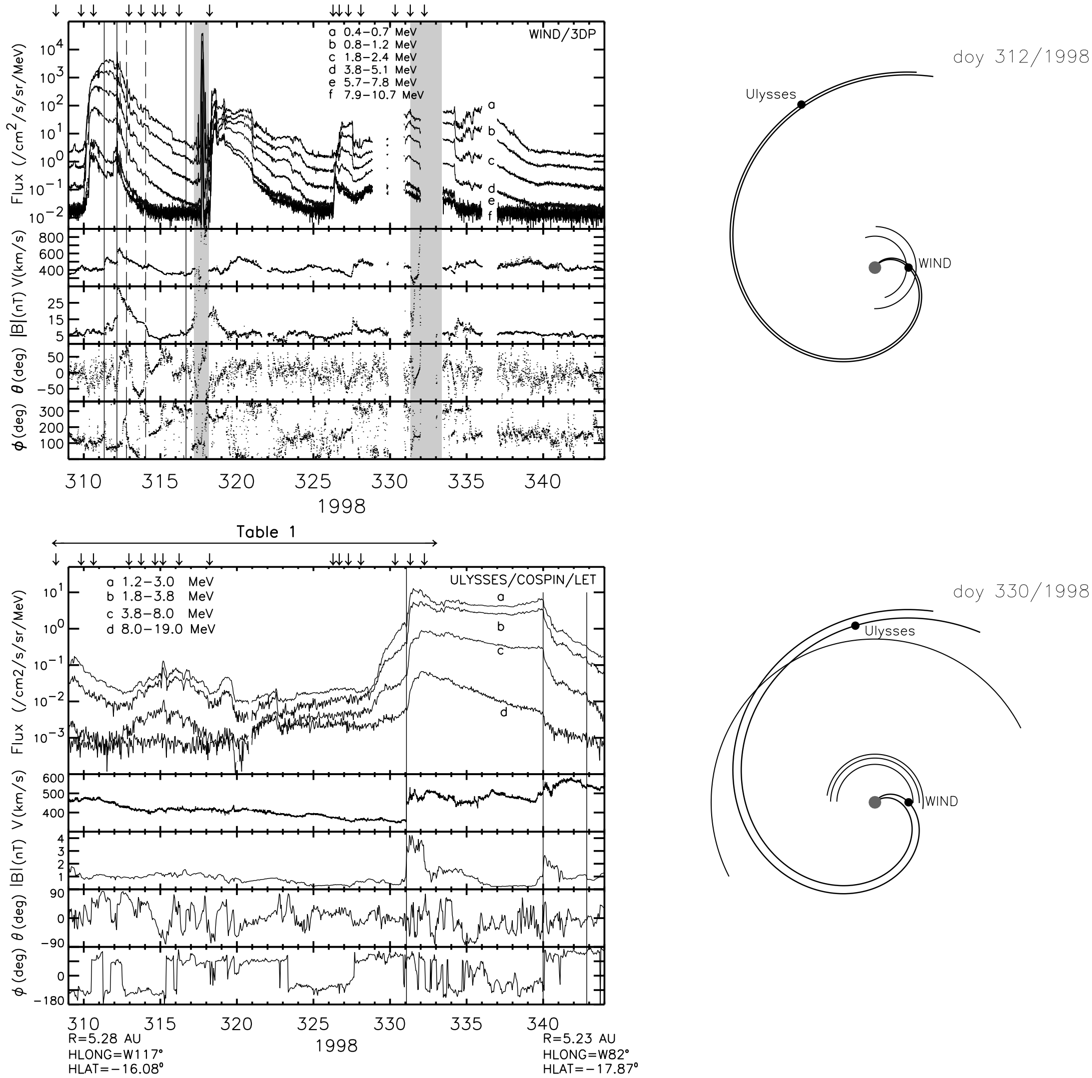

Figure 2: *Top left panel:* WIND observations: flux of 400 keV-10.7 MeV protons as measured by the semiconductor telescopes (SST) of the WIND/3DP instrument, solar wind speed (V), magnetic field magnitude ($|B|$) and its direction (θ is the polar angle and ϕ the azimuth angle in a GSE coordinate system). *Bottom left panel:* Ulysses observations: flux of 1.2-19 MeV protons as measured by Ulysses/COSPIN/LET instrument, solar wind speed, magnetic field magnitude ($|B|$) and its direction in the Ulysses RTN coordinate system. Interplanetary shocks are indicated by solid vertical lines and the boundaries of magnetic clouds or ejecta by dashed vertical lines. *Right panels:* View of the ecliptic plane as seen from the north ecliptic plane on day 312 (left) and 330 (right). See text.

ven by the CME at 309/2044 UT gets disconnected from Ulysses and do not contribute anymore to the observed proton flux. (3) The energetic particle population observed by WIND suffers significant deceleration during their transport out to 5 AU. Or finally, (4) the magnetic connection between Ulysses and WIND was not so well established as the right top panel of Figure 2 indicates.

The solar event at 318/0508 UT took place from the west limb of the Sun which, in principle, was very close to the root of the IMF line connecting to Ulysses. The onset of the associated SEP event was observed by Ulysses on day 320, but again with a lesser intensity than at WIND. The increase of the proton flux was accentuated two days before the arrival of a strong shock at 331/0146 UT. After the shock passage, the proton flux kept on increasing until a maximum of proton intensity at the end of day 331. Low-energy proton flux

Table 1: Reported solar events during November 1998

Time Flare [UT]	X-ray class	Location	Time CME [UT]	CME direction of propagation
308/0317	long-duration C5.2	AR 8375 N17°E01°	308/0418	Halo
309/1335	M1.5	AR 8375 N15°W17°	–	–
309/1825	M3.7	–	–	–
309/1955	long-duration M8.4	AR 8375 N22°W18°	309/2044	Halo
310/1511	M1.7	AR 8375 N15°W32°	–	–
311/1106	M2.4	–	–	–
312/1714	M2.7	AR 8375 N19°W58°	–	–
312/2248	M1.1	AR 8375 N21°W61°	–	–
313/∼2300	FD	Northwest limb	313/2054	W
314/1545	M1.8	AR 8375 N23°W77°	314/1418	W
315/0407	M1.0	–	–	–
315/1016	M1.1	–	–	–
316/0528	M1.0	AR 8385 N21°W34°	316/0554	W
318/0508	C1.3	AR 8375 ∼W117°	No LASCO observations	
320/2151	C4.9	AR 8383 S14°W29°	No LASCO observations	
326/0642	X3.7	AR 8384 S27°W82°	No LASCO observations	
326/1623	X2.5	AR 8384 S30°W89°	No LASCO observations	
327/0642	X2.2	AR 8384 S28°W89°	No LASCO observations	
328/0220	X1.0	AR 8384 ∼W99°	328/0230	Halo
331/0741	M1.6	AR 8392 S24°E09°	–	–
332/0609	long-duration X3.3	AR 8395 N17°E32°	332/<0830	E

remained at an approximate constant value for more than 8 days until the arrival of a second shock at 339/2353 UT. High-energy proton flux profile was already decaying before the arrival of this second shock. We suggest the following scenario to explain these observations. The solar source of the CME at 318/0508 UT was well aligned to generate a shock observed by Ulysses. The association between this CME and the shock at 331/0146 UT gives an average transit speed of 708 km s^{-1}. Before the arrival of this shock, the second series of solar events from AR 8384 took place. Particles injected from these events filled the downstream region of the first shock. Bottom right panel of Figure 2 sketches the location of this shock on day 330. The sequence of solar events from AR 8384 generated several shock fronts (plotted in the figure) which merged into one when arriving at Ulysses. The association between these solar events and the shock observed by Ulysses at 339/2353 UT gives an average transit shock speed of $\sim$760 km s^{-1}. That represents two shocks propagating at similar speeds with an energetic particle population trapped between them. The distortion of IMF lines at the downstream region of the first shock may allow a direct magnetic connection between the two shocks. Energetic particle population may bounce back and forward between the two shocks and may also undergo reacceleration processes at the front of the two shocks. We point out also the region of very low IMF magnitude between days 336 and 338 favorable for particle trapping.

3 Conclusions

During the years 1997 and 1998 the Ulysses and WIND spacecraft detected several intense SEP events in a close temporal association. However, detailed particle observations reveal that particle flux profiles at 1 and 5 AU may be quite different. This is the case for the events of November 1998. WIND observed three particle flux enhancements which were closely related to intense solar events occurring at the Sun. Ulysses observations agree more with a description based on a series of propagating structures (driven by CMEs) which determined the final shape of the observed flux profiles.

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