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# Ulysses and WIND Particle Observations of the November 1997 Solar Events

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**Abstract.** The episode of intense solar activity on 4 and 6 November 1997 resulted in large and extended particle events observed by the Ulysses and WIND spacecraft. Ulysses was at a heliocentric distance of 5.34 AU, very close to the solar equator and 100° west in heliolongitude from earth. WIND was near the earth at 0.99 AU from the Sun and in the ecliptic plane. Both spacecraft detected particle events and magnetic field structures related to this intense activity. A likely scenario for these particle events is proposed. The differences in the particle intensity profiles observed by both spacecraft are explained in terms of their location with respect to the solar activity site, the existence of interplanetary structures traveling towards the spacecraft, and the nature of particle transport from the source up to the two spacecraft.

## Introduction

During the first week of November 1997 the Sun was intensively active. The most active region was NOAA 8100 which produced two X-class flares [Solar Geophysical Data, 1997]. The first was an X2/2B flare located at S14°W33° with its maximum at 0558 UT on 4 November. During this period a nearly earth-directed halo CME was observed to start between 0552 and 0608 UT by the SOHO EIT instrumentation (B. Thompson, private communication, 1998). The second flare was the strongest soft X-ray event observed in the last 5 years, an X9.4/2B flare located at S18°W63° with maximum of intensity at 1155 UT on 6 November. A fast CME moving out off the west limb was observed around the same time (B. Thompson, private communication, 1998).

We use particle and magnetic field observations from the WIND and Ulysses spacecraft to study the effects of this solar activity in the interplanetary medium. The detection at two different heliospheric positions of the associated particle events and of the interplanetary counterparts of these CMEs provides us with the opportunity to determine the large-scale structures (shocks, magnetic clouds, etc.) causing these particle events as well as their area of influence. The particle events at Ulysses constituted the first significant enhancements since the spacecraft returned to the ecliptic plane, being the most intense and extended particle events since 1993 (e.g., *Sanderson et al.,* 1995) with 3.8-8.0 MeV proton fluxes higher than $10^{-2}$ protons/cm$^2$/s/sr/MeV for more than 9 days. In the case of WIND, the particle events had the highest counting rates of any CME-associated increases observed since its launch.

## Instrumentation

The observations presented in this paper were made with the following experiments aboard the two spacecraft. The Low-Energy Telescope (LET) of the COSPIN (Cosmic Ray and Solar Particle Investigation) instrument on the Ulysses spacecraft (*Simpson et al.,* 1992) is used to examine the 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).

The 3DP instrument aboard WIND (*Lin et al.,* 1995) measures the full three-dimensional distribution of suprathermal electrons and ions from solar wind plasma to low energy cosmic rays. Here we use observations of energetic protons from the semi-conductor telescopes (SST) in the energy range from 800 keV to 13.5 MeV. We also use observations from the WIND magnetometer MFI instrument (*Lepping et al.,* 1995).

## Observations

The positions of the Ulysses and WIND spacecraft are represented in Figure 1. We have plotted two nominal magnetic field lines, one connecting Ulysses to the Sun, and the other connecting WIND to the Sun with the measured solar wind speed of 350 km s$^{-1}$. We have indicated the locations of the two main regions of solar activity and included a cartoon of the supposed large-scale structures existing at ~2200 UT on 6 November (see discussion below). SA-1 and SA-2 denote the intense solar events occurring on 4 and 6 November respectively.

### Observations at WIND

Figure 2 shows the flux of 800 keV-13.5 MeV protons as measured by the SST instrument on the WIND spacecraft from 3 to 29 November 1997. In the lower panels we show solar wind speed (V), magnetic field magnitude ($|B|$) and directions ($\theta$ is the polar angle and $\phi$ the azimuth angle in a GSE coordinate system).

Two intense solar particle events are seen at the beginning of the month. The first onset is observed around ~0600 UT on 4 November. Whereas at high energy (defined here as >4 MeV) the maximum flux is reached shortly after the onset, at low energies (<1 MeV) it coincides with the passage of a strong shock at 2219 UT on 6 November (vertical solid line in Figure 2). Shortly after the passage of this shock (designated as S-1 and identified by R.P. Lepping [1998, private communication]) a magnetic cloud (MC-1) arrives at

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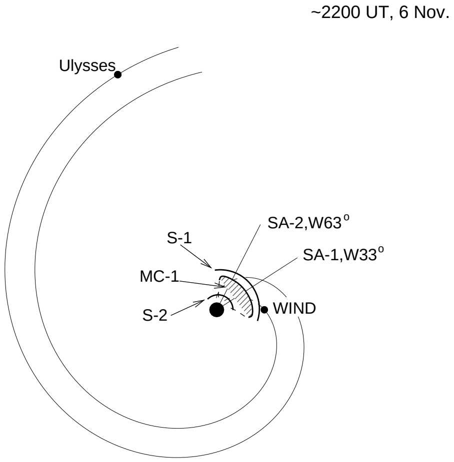

**Figure 1.** Large-scale configuration of the ecliptic plane at ~2200 UT on 6 November 1997 (see text).

WIND at 0500 UT on 7 November (vertical dashed lines in Figure 2). This structure is clearly seen in the rotation of the magnetic field direction and has been identified as a magnetic cloud by R.P. Lepping (private communication, 1998).

Before the arrival of S-1, however, a new particle enhancement was observed. High-energy proton fluxes start increasing again at ~1200 UT on 6 November. Two solar energetic particle events are easily identified in the high-energy profiles (E1 and E2 in Figure 2), but the proton profiles at low energies (<1 MeV) appear as one event extending over several days. Later on, at the beginning of 10 November, there is an abrupt decrease of proton intensities in all energy channels which occurs simultaneously with a slight rotation of the magnetic field. Two additional particle events (E3 and E4) are related to solar events which will not be discussed further in this paper.

## Observations at Ulysses

Figure 3 shows, for the same period as WIND, the flux of 1.2-19 MeV protons as measured by the LET experiment. Lower panels show the solar wind speed (V), magnetic field magnitude (|B|) and directions of the magnetic field in the Ulysses RTN coordinate system.

A long-duration particle event dominates this period. The absence of a recurrent pattern in the particle flux at these energies during the previous and following solar rotations, as well as the high value (~80) of the ratio between 1.3-3.8 MeV protons and 1.9-3.7 MeV alpha particles measured by the LET instrument (not shown here) suggest that this is not a corotating particle event.

There is some indication that the onset of the particle enhancement occurs in the middle of 7 November. However, the main onset takes place simultaneously in all channels at the start of 9 November in association with a sector boundary crossing (seen in the change of the magnetic field direction). A first maximum of flux is reached at the beginning of 11 November. A weak shock is observed at 1225 UT on the same day (vertical solid line indicated by S-2 in Figure 3). Around ~0830 UT on 13 November there is an abrupt increase in flux, occurring simultaneously in all the energy channels. This increase coincides with the beginning of a field rotation which lasts until ~1230 UT on 16 Novem-

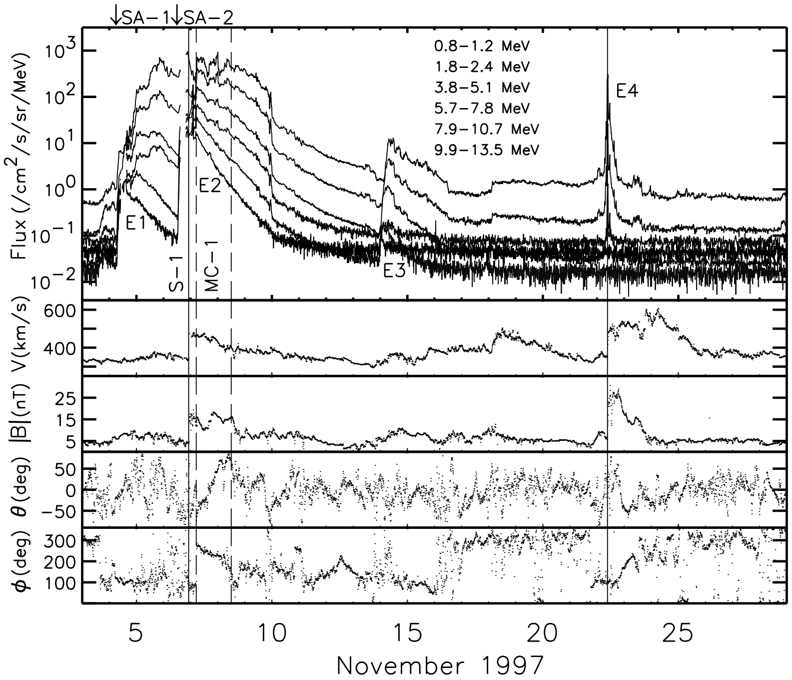

**Figure 2.** Top panel: 10-minute averages of proton intensities at energies from 0.8 to 13.5 MeV as measured with WIND/3DP-SST. The following panels show solar wind speed, magnetic field magnitude and directions. Vertical solid lines mark shock passages and dashed lines the time-interval of the magnetic cloud. E1, E2, E3, E4 indicate the different particle enhancements, and SA-1 and SA-2 the main solar events of 4 and 6 November 1997 (see text).

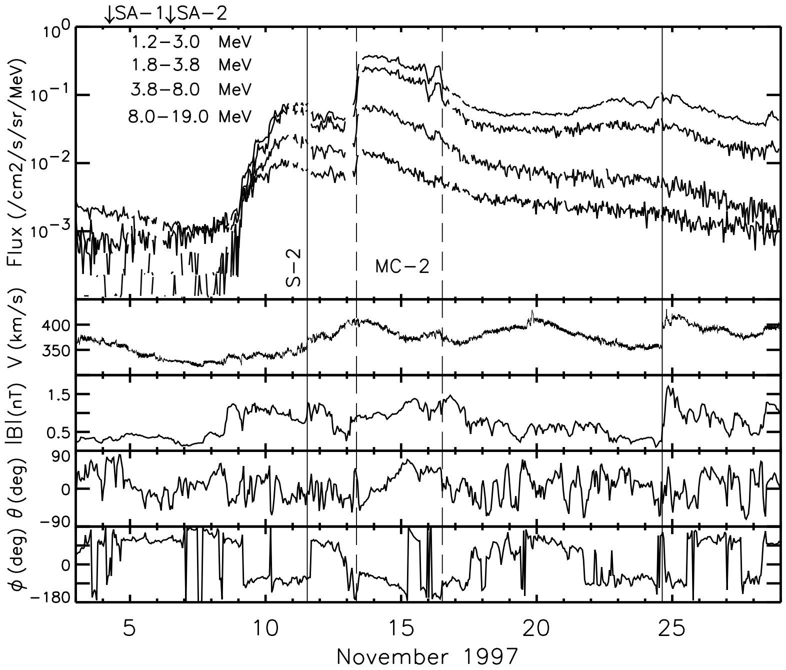

**Figure 3.** Top panel: 1-hour averages of proton intensities at energies from 1.2 to 19.0 MeV as measured with Ulysses/LET. The following panels show solar wind speed, magnetic field magnitude and directions. Vertical solid lines indicate shock passages and dashed lines the time-interval of the magnetic cloud.

ber (vertical dashed lines in Figure 3). This structure (designated as MC-2), with a slightly enhanced magnetic field and bidirectional electron fluxes (not shown here) is identified as a magnetic cloud. The whole period of magnetic field rotation is characterized by a high intensity of particles. After MC-2 the particle intensity slowly decreases, until 21 November when the flux below 3.8 MeV starts to increase gradually, with a maximum coinciding with the arrival of a shock at 1508 UT on 24 November (vertical solid line in Figure 3). The effects of this shock are not noticeable in the proton fluxes above ~4 MeV, which continue to decrease. The origin of this shock will not be discussed in this paper.

## Discussion

The particle events observed by WIND are well correlated with the intense solar activity occurring earlier at the Sun. The favorable WIND position, the time coincidence after SA-1 and the shape of the low-energy particle flux profiles of the event E1, are compatible with an interplanetary shock (S-1) driven by the CME associated with SA-1. Figure 1 sketches the large-scale structure of the shock S-1 in the ecliptic plane before arriving at WIND. MC-1 represents the CME driving this shock. S-1 accelerates particles as it propagates from the Sun to WIND. It was able to accelerate high-energy particles when it was close to the Sun, but when arriving at WIND only low-energy (<1 MeV) shock-accelerated particles are observed in association with its passage (*Heras et al.*, 1995).

Energetic particles injected from SA-2 and its associated CME constitute event E2. In Figure 1 we have drawn the shock driven by this CME (S-2) as it starts propagating from the Sun. We believe that this shock is able to fill the cloud MC-1 with energetic particles as well as the open magnetic flux tubes around MC-1. When WIND crosses the cloud MC-1, there are no significant changes in the evolution of the particle intensities, especially at high energies. Although some of the particles within MC-1 may be trapped there since SA-1 took place, the main part of this particle population is most likely accelerated by S-2, which probably is injecting particles into the edges of MC-1 (similar scenarios are presented by *Richardson and Cane,* 1996). Some of the energetic particles injected by S-2 may remain trapped in the complex magnetic field configurations behind S-1 (*Vandas et al.,* 1996) or may arrive at WIND even before S-1, as evidenced by the high energy particle observations.

Given the proximity between the flux tubes connecting WIND and Ulysses, assuming that they describe Archimedian spirals (see Figure 1), one may suppose that particles flowing past WIND will be observed later by Ulysses. However, the structure of two particle events seen by WIND (E1 and E2) is not observed by Ulysses. We suggest that propagation effects of energetic particles and magnetic structures, as well as the Ulysses location with respect to WIND, are

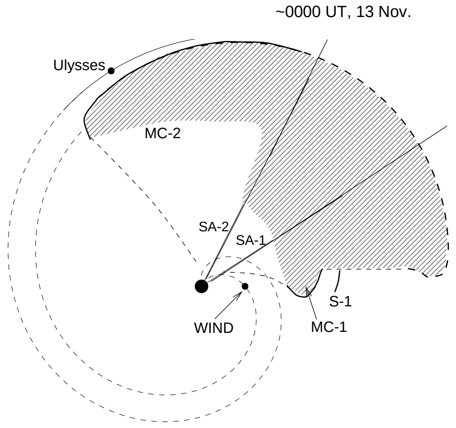

**Figure 4.** Large-scale configuration of the ecliptic plane at ~0000 UT on 13 November 1997 (see text).

the main factors responsible for the different flux profiles. Energetic particles arriving at Ulysses do not show velocity dispersion with energy. That indicates a non-direct propagation from their source to Ulysses; i.e., they may suffer numerous scattering processes at magnetic field irregularities which, at such large distances, may be of the same scale as the underlying large-scale magnetic field and may distort the Archimedian spiral structure. The sector boundary seen on 9 November and the rotation of the magnetic flux tubes along which particles propagate may also have a significant effect on the particle profiles at Ulysses. Both SA-1 and later SA-2, together with their associated shocks, are able to fill the magnetic flux tubes that will be crossed by Ulysses some time later.

We now consider the likely origin of the structures observed at Ulysses. Assuming that shock S-1 traveled at the same radial transit speed as it traveled to WIND (~645 km $s^{-1}$, assuming that it was launched at the same time as the associated CME, and was of sufficient angular extent), it would have arrived at Ulysses on 18 November. However, at that time, the cloud MC-2 had already passed the Ulysses position. It seems therefore quite improbable that MC-2 has the same origin as MC-1. The scarcity of intense solar activity before the first week of November 1997 [Solar Geophysical Data, 1997], the lack of structured and bright CMEs observed by SOHO/LASCO instrumentation before SA-1 [see LASCO CMEs list on ftp://lasco6.nascom.nasa.gov/pub/lasco/status/], and the fact that the CME associated with SA-2 was classified as bright, fast and wide in the LASCO CME list, suggest the possibility that MC-2 is associated with SA-2. The location of SA-2 with respect to Ulysses (separated only 37° in longitude) and the high velocities deduced from the associated kilometric type II emission (M.J. Reiner, private communication, 1998) and from LASCO observations, support this. In that sense, MC-2 traveled faster than MC-1, at least in the direction going to Ulysses. When a faster shock (e.g., S-2 driven by MC-2) runs into a slower cloud (MC-1) it may penetrate it and deform it (*Vandas et al.*, 1997). In this case, MC-1 would be accelerated while S-2 decelerated and deformed. Once shock S-2 crossed MC-1, cloud MC-2 would have caught up MC-1 and interacted with it, producing a new deformation of the cloud MC-1. Figure 4 shows the interplanetary configuration when MC-2 was reaching Ulysses. The shaded region represents the perturbed region that resulted from the interaction between the two clouds. In the regions where interaction presumably did not occur, original structures maintained their identity (indicated by solid lines in Figure 4). The weakness of the shock S-2 when arriving at Ulysses may be due to its deformation and deceleration when it crossed MC-1, the large distance that it had to travel to reach Ulysses, the fact that it was not intercepted through its nose, or the fact that the two-cloud interaction was not able to drive a strong shock when it was arriving at Ulysses.

The passage of the cloud MC-2 through the Ulysses position is characterized by a high intensity of particles. After SA-2 there are no intense solar events able to fill MC-2 [Solar Geophysical Data, 1997]. We suggest, therefore, that the origin of these energetic particles must be related to SA-1 and SA-2. It is possible that particles observed within MC-2 were trapped at the Sun and carried out with the structure. The expansion of MC-2, and the uncertain origin of such particles makes this unlikely, however, Figure 4 depicts another scenario to explain their origin. Particles injected by S-1 when it was closer to the Sun enter MC-2 after they have traveled along the interplanetary magnetic field lines. The entry of particles into this cloud is restricted by the highest energy which S-1 is able to accelerate and by the ability of the particles to reach and overcome the magnetic field discontinuities at the limits of the cloud. On the other hand, we cannot rule out the possibility that those particles injected by S-1 into its downstream region and those particles that were inside MC-1, when traveling towards the Sun, may mirror and enter MC-2.

## Conclusions

We have presented a possible scenario to explain particle observations by the WIND and Ulysses spacecraft related to the episode of intense solar activity that occurred in November 1997. WIND saw two particle events associated with SA-1 and SA-2 and a strong shock related to SA-1. Ulysses saw a combination/superposition of the two particle events but only a magnetic cloud which constituted the more distant interplanetary counterpart of a CME seen in the ecliptic plane. The large-scale structure of this cloud was probably formed by the interaction of the two associated clouds or a deformed structure of them.

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