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Energetic proton observations at 1 and 5 AU
1. January–September 1997

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Abstract. We present energetic particle observations by the Ulysses and Wind spacecraft during the years 1997–1998. During this period, Ulysses moved from $+19°$ to $-19°$ in heliographic latitude with heliocentric distances ranging from 4.71 to 5.41 AU. Wind was located near the Earth at 1 AU from the Sun in the ecliptic plane. The proximity of Ulysses to the ecliptic plane allows us to compare proton fluxes at different heliospheric distances and heliolongitudes but at similar latitudes. Enhancements in the energetic (approximately MeV) MeV proton fluxes were observed by both spacecraft in a close temporal association. We quantify this temporal coincidence and we distinguish two time intervals based on the energy range of the proton flux increases and on the solar wind streams observed by the Ulysses spacecraft. Each one of these two periods (period 1, January–September 1997 and period 2, October 1997 to December 1998) corresponds also to a different level of solar activity. We establish a direct correspondence between individual particle flux enhancements observed by both spacecraft throughout period 1. At 1 AU the proton flux enhancements are associated with the occurrence of coronal mass ejections (CMEs) at the Sun. At 5 AU the presence of high-speed solar wind streams, the contribution of energetic particles from CMEs, and the evolution of the magnetic field structures along which energetic particles propagate determine the final shape of the proton flux enhancements and their time delays with respect to 1 AU. When a solar energetic particle (SEP) event is observed at 1 AU, particle flux enhancements associated with recurrent high-speed solar wind streams at ~5 AU show a higher particle flux intensity. We suggest that SEPs accelerated by CME-driven shocks act as a background seed particle population available to be reaccelerated by shocks associated with corotating high-speed streams.

1. Introduction

During solar minimum conditions the near-ecliptic heliosphere is dominated by corotating high-speed solar wind streams that originate in coronal holes and are separated by lower-speed solar wind originating from the equatorial streamer belt [*Gosling et al.*, 1981]. Interaction between slow and fast solar wind occurs when fast solar wind streams overtake slow solar wind, creating a corotating interaction region (CIR) of compressed heated plasma at the leading edge of the high-speed stream. At low heliographic latitudes, such CIRs are typically bounded by forward and reverse waves on their leading and trailing edges, respectively, that steepen into shocks at large heliocentric distances [*Hundhausen and Gosling*, 1976]. Acceleration of protons up to ~20 MeV energies occurs at both of these shocks [*Barnes and Simpson*, 1976; *Sanderson et al.*, 1994]. Interplanetary spacecraft near Earth detect recurrent increases in the intensities of energetic (<1 MeV) protons during periods of low solar activity [*Bryant et al.*, 1963]. Anisotropies in the arrival direction of these particles [*Richardson et al.*, 1993] and the increasing intensity of CIR-associated ion enhancements with heliocentric distance out to 1 AU [*Kunow et al.*, 1977] confirm that the protons are accelerated in the outer heliosphere and stream toward the Sun along the magnetic field [see *Richardson et al.*, 1993, and references therein].

The number of particles accelerated by these CIR shocks depends, in principle, on the characteristics of the shocks and on the seed particle population available for acceleration (see *Desai et al*. [1999] for a discussion). *Richardson et al*. [1993] examined the energetic particle flux enhancements observed at the heliocentric distance of 1 AU in association with corotating high-speed solar wind streams. They found that the ion intensity was not correlated with the speed of the solar wind stream, suggesting that the local shock strength alone did not play a dominant role in determining the ion intensity of the particle flux enhancement. *Desai et al*. [1998] point out that the absence of a correlation between shock strength and particle intensity of CIR events observed in the ecliptic plane by the Ulysses spacecraft was due to variations in the background seed particle population coming from transient solar events. *Richardson et al*. [1993] excluded in their study those streams contain-

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ing ions associated with solar energetic particle (SEP) events and traveling interplanetary shocks; therefore the presence of a background low-energy SEP source population for CIR-shock acceleration was not explicitly considered.

The analysis of specific particle events observed simultaneously by two spacecraft, one at a location dominated by the effects of solar wind CIR structures and the other dominated by the effects of a transient traveling interplanetary shock, confirms that an SEP population may contribute to the processes of particle acceleration at CIR shocks. For example, *Richardson et al*. [1998] analyzed the recurrent particle events observed simultaneously at 1 AU by IMP 8 and at ~3–5 AU by Ulysses from mid-May to mid-November 1991. Whereas at 1 AU the particle events were associated with transient solar events, at ~3–5 AU they were associated with CIR shocks. They suggested that the recurrent events at Ulysses were produced when particles associated with solar events populated those interplanetary magnetic field (IMF) lines connected to Ulysses where CIR shocks reaccelerated the SEP population [*Richardson et al*., 1998].

Element abundances of energetic particles observed in SEP and CIR events have been used to distinguish the origin of the particle population [*Reames et al*., 1991; *Reames*, 1999]. Particles in SEP events are accelerated from the ambient material in the corona or solar wind by shock waves driven by large coronal mass ejections (CMEs). Their abundances reflect the abundances in the solar corona and low-speed wind where CMEs more likely drive shocks. For those energetic particles associated with CIRs the abundances are close to the solar wind values averaged between the high- and slow-speed solar wind streams [*Mason et al*., 1997]. The SEP contribution to the processes of CIR-shock acceleration has also been observed in some specific particle events. On the basis of their more SEP-like ion abundances, *Maclennan et al*. [1993] and *Franz et al*. [1995] noted that the recurrent CIR events observed by Ulysses in the period May–November 1991 included contributions from the SEP events observed simultaneously at 1 AU [*Richardson et al*., 1998].

Observations of CIR-associated particle events during periods of intense SEP production are important for understanding the origin of the seed particle population in CIR-shock acceleration mechanisms. The first half of 1997 offers us an excellent opportunity to perform this study. Ulysses was moving toward the ecliptic plane from regions dominated by high-speed solar wind streams to the streamer belt dominated by the slow solar wind [*Sanderson et al*., 1999]. Simultaneously, those spacecraft located around the orbit of the Earth started observing SEP events associated with the occurrence of CMEs at the Sun [*Cane et al*., 1998]. There were very few energetic CMEs throughout the first half of 1997 [*Cane et al*., 1999] that helped to preserve the recurrent CIR structure observed by Ulysses during its journey to ecliptic latitudes. From the second half of the year 1997, however, Ulysses remained immersed in the slow solar wind. Moreover, the increasing level of solar activity resulted in the occurrence of successive large CMEs that drove shock waves through the interplanetary medium distorting the preexisting magnetic field and plasma configuration of the heliosphere. Particle and solar wind data from the Ulysses spacecraft allow us to distinguish these two well-differentiated periods and to investigate the conditions under which these energetic particles propagated to Ulysses. In section 2 we present the energetic particle observations by the Ulysses and Wind spacecraft during the years 1997–1998. We compare the proton flux profiles at both spacecraft, and we distinguish these two periods. In section 3 we describe the fact that the proton flux enhancements were observed in a temporal coincidence at Wind located at 1 AU and at Ulysses located at ~5 AU, in spite of the large longitude and radial distance between both spacecraft. Finally, in section 4 we establish a correspondence between specific and individual particle events observed at both spacecraft during the first time interval, paying special attention to those periods when an SEP event was observed at 1 AU and a CIR event at ~5 AU. In a following paper [*Lario et al*., this issue, hereinafter referred to as paper 2] we analyze the characteristics of the particle events from the second half of 1997 and throughout the rising phase of the solar cycle 23.

2. Observations

Ulysses particle observations presented in this paper were made with the Low Energy Telescope (LET) of the Cosmic Ray and Solar Particle Investigation (COSPIN) instrumentation [*Simpson et al*., 1992]. We use the 10 min 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]. Ulysses data analyzed in this paper cover the 2-year period 1997 and 1998. In January 1997 the Ulysses spacecraft was at a distance of 4.71 AU from the Sun, at a heliographic latitude of 19°N, and at a heliolongitude of W53° with respect to the Sun–Earth line. It was moving south reaching aphelion in April 1998 at 5.41 AU from the Sun and at a heliolongitude of E54°. At the end of December 1998 the spacecraft was located at a distance of 5.20 AU from the Sun, heliographic latitude of 19°S, and heliolongitude of W61° with respect to the Sun–Earth line.

Observations close to 1 AU were made with the 3*DP* instrument aboard Wind [*Lin et al*., 1995]. This spacecraft executed complex orbits between the Earth and the Lagrangian point (L1) spending most of the time in the solar wind [*Sanderson et al*., 1998]. In November 1998, Wind was placed in a new petal orbit around the Earth with a $\sim 10\ R_E$ perigee and $\sim 80\ R_E$ apogee, which allowed consecutive encounters by the Wind spacecraft with the Earth's magnetosphere. We use observations of energetic protons in the energy range from 400 keV to 13.5 MeV. Although the 3*DP* instrumentation did not resolve protons from alphas and heavier ions, their contribution (small compared to the influence of the more numerous protons) does not affect the description of the particle events included in this paper. We also use observations from the Wind magnetometer MFI instrument [*Lepping et al*., 1995].

Figure 1 shows the proton flux observations by the Wind and Ulysses spacecraft throughout 1997 and 1998. Figure 1 (top) shows 1-day averaged 1.8–3.8 MeV proton fluxes observed by Ulysses (thick trace) and 1-day averaged 1.8–2.4 MeV proton fluxes observed by Wind (thin trace; scaled up two orders of magnitude). Figure 1 (bottom) 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; scaled up 2 orders of magnitude). In broad terms, the Wind and Ulysses profiles are remarkably similar, which, in principle, is an unexpected result in view of the large heliolongitude and radial separation existing between the two spacecraft throughout the 2-year period.

The instrument configuration is such that, at quiet times, the COSPIN/LET 8–19 MeV proton channel responds mainly to

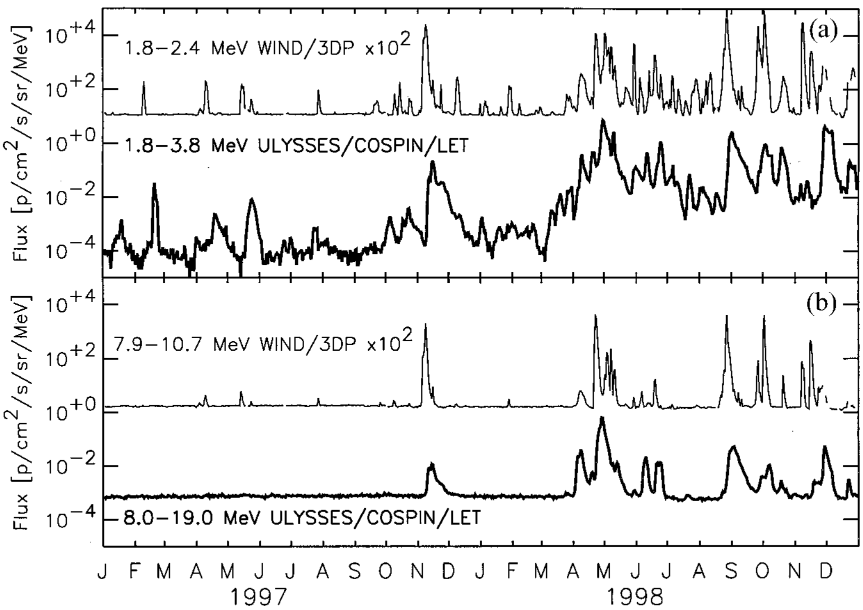


Figure 1. Daily averaged fluxes of (a) 1.8–2.4 MeV and (b) 7.9–10.7 MeV protons observed by Wind (thin traces) and (a) 1.8–3.8 MeV and (b) 8.0–19.0 MeV protons observed by Ulysses (thick traces) for 1997 and 1998. Wind proton fluxes are scaled up 2 orders of magnitude.

galactic cosmic rays, but when the level of solar activity increases, it also responds to solar particles, so it can be used as a measure of intense solar activity. Early in 1997, no increases were 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 long-lasting particle events in April–May 1998, August 1998, and November 1998; the two peaks during June 1998; and the proton flux enhancement at the beginning of October 1998 (see paper 2 for their association with specific transient solar events).

The high-energy (7.9–10.7 MeV) proton Wind profile (Figure 1b) shows the same trend as the Ulysses proton profile, with the same periods of high proton intensity. At lower energies (1.8–2.4 MeV) the proton Wind profile (Figure 1a) shows a larger number of particle flux enhancements, particularly from October 1997 onward. It is worth pointing out that the instrumental background of the Wind/3*DP* experiment in all energy channels prevents us from seeing the real onset of these particle events, creating a fictitious flat profile during quiet times (see discussion for specific particle events in section 4).

The low-energy (1.8–3.8 MeV) proton Ulysses profile shows a more irregular shape. Early in 1997, enhancements in particle flux were almost recurrently observed, usually with a short time duration (no longer than ~13 days) and with low-intensity maxima (excluding the peaks in February and May 1997). The profile changed drastically in October 1997 when high proton flux enhancements started being observed over long time intervals. The particle onset in March–April 1998 deserves special mention as the flux increased more than 4 orders of magnitude during 2 months. New injections of particles seemed to sustain a very high particle intensity that did not return to background levels throughout the rest of the period under study.

Even given the existence of a high instrumental background level in Wind profiles, the day-to-day variations observed at 1 AU are larger than at 5 AU. Proton fluxes show more structure and are more abrupt at Wind than at Ulysses. For example, *Lario et al.* [1998a] studied the particle events in November 1997; at 1 AU, several particle flux increases were observed in association with specific CMEs, but at 5 AU, Ulysses only observed a broad proton flux enhancement lasting more than 20 days. Interplanetary processes acting upon the particles from 1 to ~5 AU are responsible for broadening the proton flux profiles observed in the outer heliosphere [*Roelof et al.*, 1992]. Differences between high- and low-energy profiles suggest that those processes act more strongly on low-energy protons than on high-energy protons (see paper 2). High-energy particle observations (Figure 1b) allow us to distinguish two clear time intervals. Period I from January 1, 1997, to September 30, 1997, characterized by a lack of high-energy proton enhancements at Ulysses and only small ($<10^{-1}$ proton/cm^{2}s sr MeV at 7.9–10.7 MeV) proton flux increases at Wind; and Period II from October 1, 1997, to December 31, 1998, when high-intensity and long-lasting particle events were observed.

Figure 2 shows 1-hour averaged 1.8–3.8 MeV proton flux, plasma proton temperature, solar wind speed, plasma ion density, and magnetic field magnitude as observed by Ulysses for Period I. At the beginning of 1997, Ulysses was moving down from the region dominated by the high-speed solar wind originating from the polar coronal holes, into the slow solar wind coming from the streamer belt [e.g., *Gosling et al.*, 1997]. The observation of several large recurrent high-speed solar wind streams at Ulysses was due to the combined effect of the rotation of the tilted heliosphere current sheet and an equatorward extension of a polar coronal hole [*Sanderson et al.*, 1999]. Each one of these excursions in and out of the low-speed flow has been numbered by *Sanderson et al.* [1999] as indicated in Figure 2c. The typical plasma and magnetic field signatures of the corotating high-speed solar wind streams have been described elsewhere [see, e.g., *Richardson et al.*, 1993]. The leading edge is expected to be characterized by increases in the

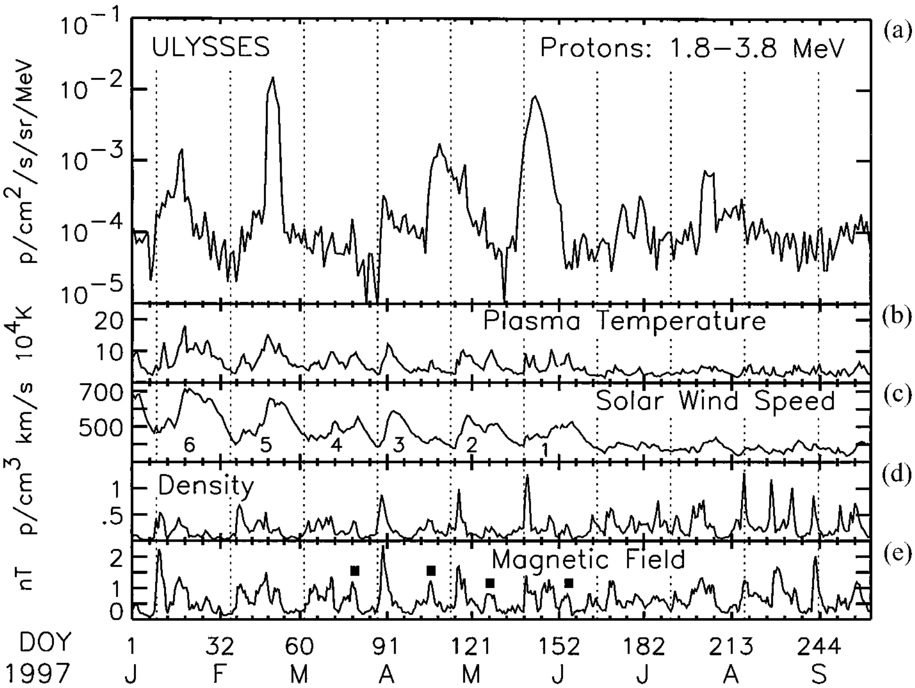


Figure 2. One-day averages of (a) 1.8–3.8 MeV proton flux, (b) plasma ion temperature, (c) solar wind speed, (d) plasma ion density, and (e) magnetic field magnitude as observed by Ulysses throughout period 1. The numbers in Figure 2c indicate each one of the excursions in and out of the low-speed solar wind flow. The black square in Figure 2e indicates the recurrent compression region arriving at Ulysses. The vertical dotted lines are spaced 26 days apart.

plasma density, temperature, and magnetic field intensity. The trailing edge is characterized by decreases in the plasma density, temperature, and magnetic field intensity. All these features are observed in the labeled (1–6) high-speed streams. We point out that the last four streams show a secondary peak with a high magnetic field magnitude, indicated by a black square in Figure 2e. In July 1997, Ulysses finally became fully immersed in slow-speed flow, while some excursions to compression regions of high plasma ion density and magnetic field magnitude were still observed.

Several low-energy proton flux enhancements are observed during period 1, but they do not show a clear recurrence associated with the arrival of the high-speed streams. The first two peaks in January and February 1997 seem to be associated with the high-speed streams 6 and 5, respectively, but their intensities and proton-to-alpha ratios [see *Sanderson et al.*, 1999] are quite different. High-speed streams 4 and 2 do not present a clear particle onset. The main particle onset for the high-speed stream number 3 seems to be associated with the secondary peak indicated by a black square, even though the leading edge of this stream shows a high magnetic field magnitude. The particle enhancement associated with the high-speed stream number 1 shows a very high intensity during a long time interval (~11 days) and proton-to-alpha ratios characteristic of a particle event of solar origin [*Sanderson et al.*, 1999]. Finally, in July 1997, there is a small flux increase that seems to be associated with a compression region of magnetic field and density plasma. Comparison of these proton flux enhancements with Wind particle observations will be discussed in section 4.

Figure 3 shows Ulysses observations (with the same parameters as Figure 2) for period 2. Solar wind speed remains low for the whole period with the exception of the increases at the end of November 1998 related to a transient event and in May 1998. Plasma ion density and magnetic field magnitude show also several excursions to high values that are associated with interplanetary shocks arriving at Ulysses. Particle observations and the effects of these shocks on particle population are discussed in paper 2.

Energetic particle observations as well as plasma and magnetic field data support the distinction between period 1 and period 2. In period 1, Ulysses plasma and magnetic field observations follow an approximate recurrent pattern with repeated transitions from fast to slow solar wind. In period 2, no pattern was apparent and solar wind was predominantly slow. That suggests that a different set of processes was responsible for the production of energetic particles seen at Ulysses during the two periods as well as different heliospheric conditions under which these particles were transported to the spacecraft.

3. Propagation and Time Delays

Some of the proton flux enhancements observed by Ulysses at ~5 AU appear in temporal association with the particle events observed by Wind at 1 AU. While an initial peak at Wind seems always to be followed by a peak at Ulysses, their intensity maxima and duration are quite different (Figure 1). It is difficult to establish an expected time delay between a particle flux enhancement first seen at Wind and later at Ulysses. Several factors need to be considered: (1) the changing position of Ulysses with respect to Wind; (2) the uncertainties about the modes of particle propagation between both spacecraft; and (3) the nature, origin, and propagation of the agent that injected those energetic particles into the interplanetary

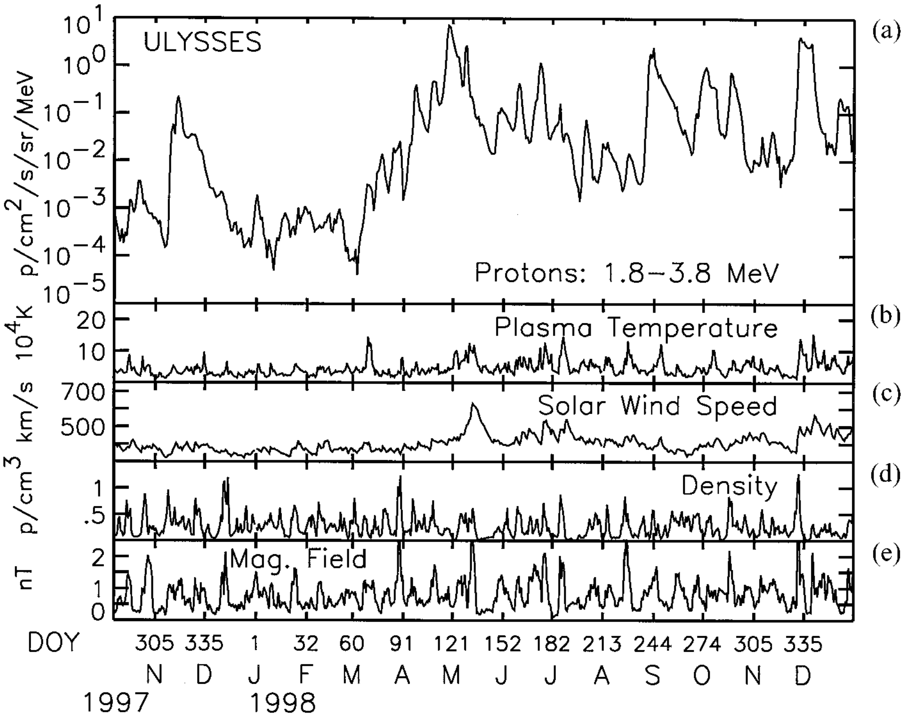


Figure 3. One-day averages of (a) 1.8–3.8 MeV proton flux, (b) plasma ion temperature, (c) solar wind speed, (d) plasma ion density, and (e) magnetic field magnitude as observed by Ulysses throughout period 2.

medium. It may even be that given particle flux enhancements observed at Wind and Ulysses have a completely independent source origin (solar or interplanetary) making the prediction of an expected time delay impossible. For those particles coming from a common source, however, the time delay depends on the effects introduced by their propagation from one spacecraft to the other. The lower limit is determined by assuming that the two spacecraft are located on the same field line and energetic protons propagate along this line under scatter-free conditions. Assuming a Parker spiral for the large-scale magnetic field structure, with solar wind speed of 400 km s^{-1}, a 2 MeV (10 MeV) proton with pitch angle equal to zero, will take ~29 (~13) hours to travel from 1 to 5 AU. An upper limit, 17.3 days, is derived from requiring that energetic protons remain trapped into a closed magnetic field configuration which moves radially at the normal solar wind speed (say 400 km s^{-1}) from one spacecraft to the other. An intermediate case is determined by assuming that the main source of particles is a traveling interplanetary shock that propagates radially from one spacecraft to the other; taking a constant transit speed of 800 km s^{-1}, the shock takes 8.6 days to travel from one spacecraft to the other.

The motion of the magnetic field lines frozen in the solar wind is such that under steady conditions, CIR shocks appear to corotate. Corotating solar wind streams seen first by a spacecraft at the heliocentric distance of r_1 and at the heliolongitude of ϕ_1 will cross, after the appropriate time delay, another spacecraft located at a different heliocentric distance r_2 and heliolongitude ϕ_2. The corotation time delay taken by the solar wind stream to move from the first spacecraft to the second is

$$t_2 - t_1 = (\phi_2 - \phi_1)/\Omega + (r_2 - r_1)/v_{sw}, \quad (1)$$

where v_{sw} is the solar wind speed and Ω is the solar angular velocity [*Richardson et al.*, 1998]. Energetic particles propagating along the field lines contained in this solar wind stream will reach the first spacecraft at the time t_1 and, simply owing to the motion of the field lines frozen into the solar wind, will be observed by the second spacecraft at the time t_2. Those energetic particles might have been injected on to these field lines from distant sources, for example CIR shocks or CME-driven shocks. This effect, known as the corotation effect, has been studied by *Kallenrode and Wibberenz* [1997], *Lario* [1997], and *Lario et al.* [1998b] for SEP events within 1 AU. *Lario et al.* [1998b] concluded that it might be important under certain circumstances, but it is particularly relevant to observations at 5 AU, because interplanetary processes are thought to have a stronger effect on particle propagation in the outer than in the inner heliosphere [*Roelof et al.*, 1992]. Energetic particles injected from a CME-driven shock at 1 AU remain tied to a given magnetic field line along which they propagate; these particles may be observed by a distant spacecraft at 5 AU only when this magnetic field line reaches the spacecraft, which may occur after a given corotation time delay, even though the spacecraft might never have established direct magnetic connection with the traveling shock. For an observer at $r_1 = 1$ AU and $\phi_1 = 0°$ and a second observer at $r_2 = 5$ AU and $\phi_2 = 0°$, 90°, 180°, and 270°, the corotation time delay is 17.3, 24.0, 4.0, and 10.6 days respectively, assuming $v_{sw} = 400$ km s^{-1}.

The fact that a particle flux enhancement seems to be always observed first by the Wind spacecraft and later by Ulysses (Figure 1) can be quantified by correlating the time-intensity profiles of both spacecraft by using several time delays. A similar study was done by *Boufaida and Armstrong* [1997], who analyzed the correlation between the fluxes at IMP 8 and Ulysses for two periods in 1991 when Ulysses was in the ecliptic plane moving toward Jupiter with heliocentric radial distances ranging from 1.59 to 4.04 AU. They performed a standard cross-correlation analysis of the logarithms of the fluxes for

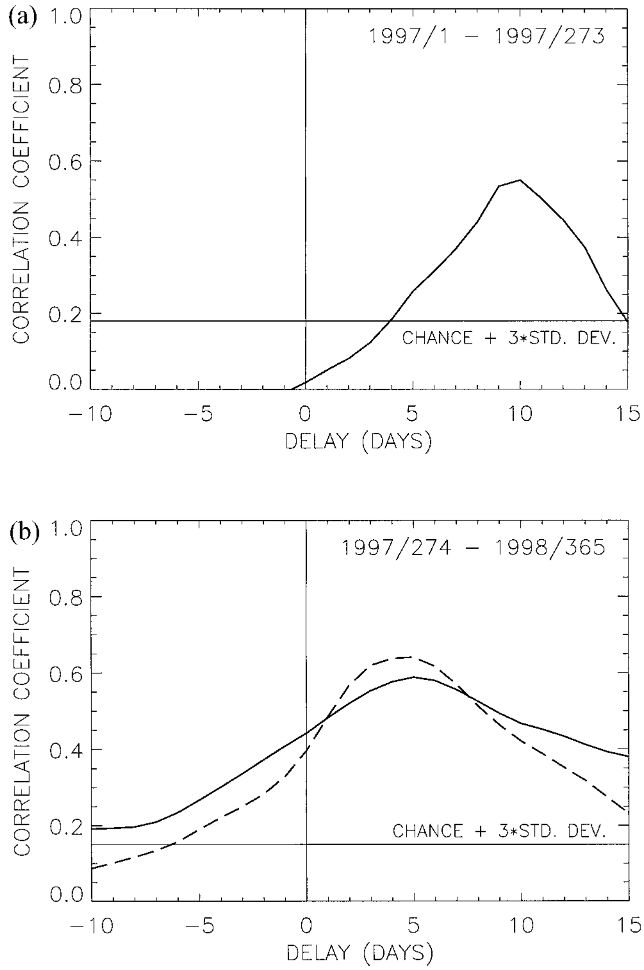


Figure 4. Cross-correlation versus time delay for low-energy (solid line) and high-energy (dashed line) protons observed by Ulysses and Wind for (a) period 1 and (b) period 2.

several time delays. They found a maximum of the correlation for 1–2 days delay, suggesting that particles propagate directly from one spacecraft to the other along magnetic field lines [*Boufaida and Armstrong*, 1997].

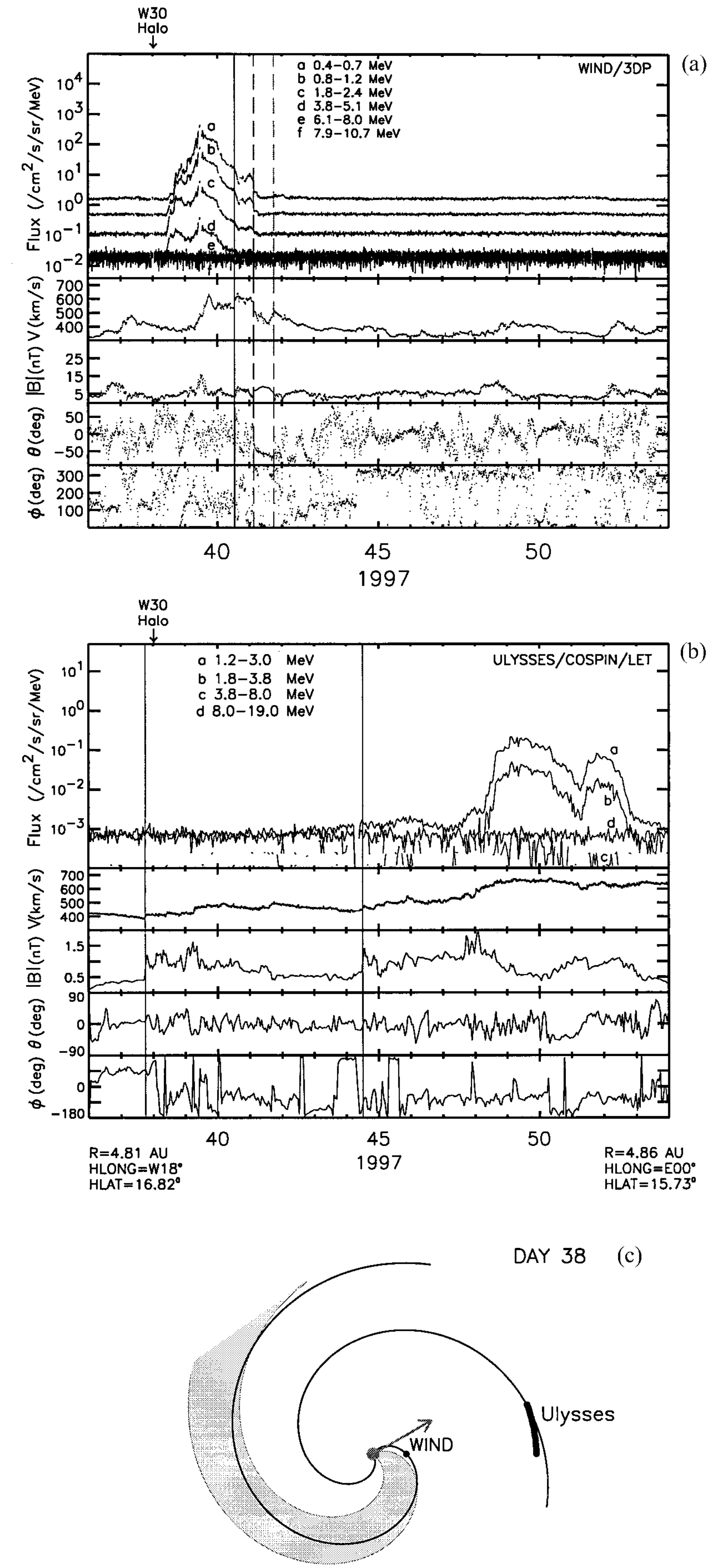
Figure 4 shows our results for period 1 (Figure 4a) and period 2 (Figure 4b). We have considered that the energy channels for Wind and Ulysses shown in Figure 1 are similar enough to compare their general profiles, assuming that the effects due to different particle velocity or energy-dependent differences in the particle populations are small. Figure 4a contains only one line corresponding to the energies of the Figure 1a because the Ulysses high-energy profile remained at background levels for the whole period 1. For period 1 the correlation peaks at delay of 10 days (correlation coefficient $\xi = 0.55$). We have established a significance level for the correlation coefficients as in the work of *Boufaida and Armstrong* [1997] by shuffling the order of the Wind fluxes 300 times and computing repeatedly their correlation with Ulysses fluxes. The "CHANCE+3. STD. DEV." line in Figure 4 marks the level of significance obtained for the distribution of correlation coefficients obtained with the shuffled data; it gives an idea of the difference between a correlation using a random particle data and using those data actually observed by Wind. For period 2 a higher correlation is found for a delay of 5 days ($\xi = 0.59$ and $\xi = 0.64$, for low and high energy, respectively) with standard deviation for the shuffled data similar to that found for period 2.

In general, short time delays between particle events at two different spacecraft are due to direct particle propagation from one spacecraft to the other. Long time delays are due to spatial structures able to inject particles and control their transport through the interplanetary medium (shocks, high-speed streams, close magnetic structures, corotation effects, etc.). Although it is not possible to have a complete knowledge of the field geometry existing for particle propagation between Wind and Ulysses, the time delays inferred from Figure 4 are not consistent with a rapid motion of protons along IMF lines connecting both spacecraft. This result is not unexpected since throughout the long periods considered in Figure 4, Ulysses changed its location with respect to Wind, and both spacecraft would rarely have been connected to the same field line: Ulysses moved eastward with respect to the Sun–Earth line from ϕ = W53° (r = 4.71 AU) in January 1997 to ϕ = W149° (r = 5.29 AU) at the end of September 1997 (passing by ϕ = E0° in February 1997) during period 1. In period 2 it moved from ϕ = W149° (r = 5.29 AU) at the beginning of October 1997 to ϕ = W61° (r = 5.20 AU) at the end of December 1998 (passing by ϕ = E0° in February 1998). It is also possible that extended source regions were responsible for injecting particles simultaneously on to those field lines connected to Wind and Ulysses and produce the particle flux enhancements observed by both spacecraft. In that case the expected time delay would depend on the different conditions under which energetic particles propagate from their source to Wind and to Ulysses. The results shown in Figure 4 do not allow us to distinguish the physical conditions under which the particle flux enhancements developed throughout the periods 1 and 2 and the source of particles responsible for the flux enhancements. It is significant, however, that period 1 gives longer time delays than period 2. Note also that the low correlation coefficients found for negative time delays suggest that the general trend is first a particle enhancement at Wind and later at Ulysses. In view of the variability of factors that influence the time delay between particle flux enhancements at both spacecraft for those long periods, we proceed to study in detail each particle onset observed at both spacecraft. We match those particle onsets observed at the two spacecraft and suggest global scenarios to explain their origin and the delay between both spacecraft (see section 4 and paper 2).

4. Scenario for the Particle Events in Period 1

Figures 5–8 show details of the selected periods. These figures correspond to those time intervals when high proton intensities were observed at both spacecraft. All figures are structured in the same way. In the top panel we present Wind observations: 10-min averages of the 400 keV to 10.7 MeV

Figure 5. (opposite) (a) Wind and (b) Ulysses observations for the February 1997 period. (c) Spatial configuration of the ecliptic plane on day 38. Nominal magnetic field lines (solid lines) have been plotted assuming a Parker spiral with a solar wind speed of 400 km s^{-1}. A solar wind speed of 600 km s^{-1} has been assumed for the high-speed stream (shaded region). The arrow shows the source longitude of the CME at 38/0030 UT. See text for details.


W30
Halo
(a)
WIND/3DP
a 0.4–0.7 MeV
b 0.8–1.2 MeV
c 1.8–2.4 MeV
d 3.8–5.1 MeV
e 6.1–8.0 MeV
f 7.9–10.7 MeV
Flux (/cm2/s/sr/MeV)
V (km/s)
|B| (nT)
θ (deg)
φ (deg)
40
45
50
1997
W30
Halo
(b)
ULYSSES/COSPIN/LET
a 1.2–3.0 MeV
b 1.8–3.8 MeV
c 3.8–8.0 MeV
d 8.0–19.0 MeV
Flux (/cm2/s/sr/MeV)
V(km/s)
|B|(nT)
θ (deg)
φ (deg)
40
45
50
1997
R=4.81 AU
HLONG=W18°
HLAT=16.82°
R=4.86 AU
HLONG=E00°
HLAT=15.73°
DAY 38
(c)
Ulysses
WIND

proton flux as measured by the semiconductor telescopes (SST) of the Wind/3*DP* instrument, the solar wind speed (V), the magnetic field magnitude ($|B|$), and its direction (θ is the polar angle and ϕ the azimuth angle in a GSE coordinate system). In the middle panel we show Ulysses observations: 1-hour averages of the 1.2–19 MeV proton flux as measured by the LET of the Ulysses/COSPIN instrument, the solar wind speed as measured by the Ulysses solar wind plasma experiment, the magnetic field magnitude ($|B|$), and its direction in the Ulysses RTN coordinate system. In the top part of each panel we indicate the main CMEs and solar flares occurring during that time interval [*Bothmer et al*., 1997; *Cane et al*., 1998; *Torsti et al*., 1998; *Berdichevsky et al*., 1998]. Interplanetary shocks are indicated by solid vertical lines and the boundaries of magnetic clouds or ejecta by dashed vertical lines. Interplanetary shocks and magnetic clouds at Wind have been identified by the Wind/MFI team (their list is accessible on http://lepmfi.gsfc.nasa.gov/).

The bottom panels of Figures 5–8 are snapshots of the spatial configuration of the Sun, and of the Ulysses and Wind spacecraft as seen from the north ecliptic pole in a coordinate system fixed with respect to the Sun–Earth line. Black dots indicate the position of both spacecraft during the interval of time plotted in the two top panels (specified in days of the specific year). Two nominal IMF lines (solid lines) connecting the Wind and Ulysses spacecraft to the Sun have been plotted using a typical measured value for the solar wind speed (indicated in the caption of each figure) and assuming a Parker spiral for the magnetic field configuration. We also show a schematic representation of the corotating interaction regions and high-speed solar wind streams (shaded areas in Figures 5–8). The time of each snapshot is indicated at the top right corner. The Sun is located at the center and plotted as a big solid circle. The arrows indicate the direction (longitude) of solar events occurring throughout the time interval under study.

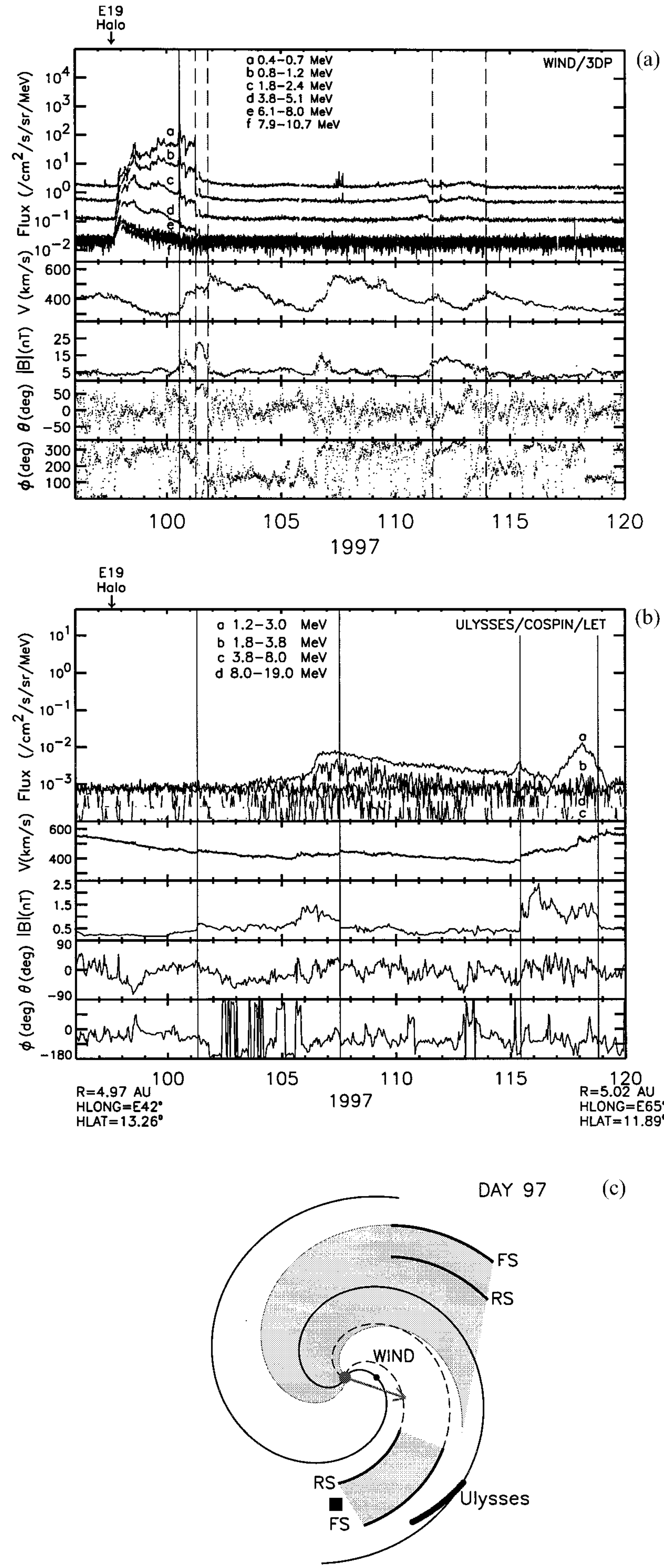
We discuss the individual particle events in chronological order. An analysis of the Wind observations in terms of the solar events occurring at the Sun is first presented. Previous studies are referred to in order to establish the association between SEP events at Wind and solar activity. That allows us to locate the main sources of particles filling the heliosphere (at least those parts scanned by Wind). Particle observations at Ulysses are then analyzed in terms of the spacecraft's location and the possible arrival of the SEPs accelerated by the CME-driven shocks or the presence of high-speed solar wind streams. The title of each subsection refers to the period of time under study. Dates are indicated by the number of day in the year 1997 followed by the universal time.

4.1. February 1997

Figure 5 shows the relative positions of Ulysses and Wind and their respective particle and field observations from day 36 to day 54 of 1997. Two energetic particle events were observed during this period, one by Wind from day 38 to day 40 and the other by Ulysses from day 48 to day 53. The particle event observed by Wind was also observed by other spacecraft around the orbit of the Earth. *Torsti et al*. [1998] and *Cane et al*. [1998] associate this particle event (using SOHO/ERNE and IMP 8 observations, respectively) with a halo CME observed by SOHO/LASCO instrumentation around 0030 UT on day 38. This CME was related to a large filament eruption observed during the first hours of the day 38. This filament had a long neutral line near a small bright active region at about S25°W30° where the origin of the eruption is located (D. Webb, private communication, 1999). An interplanetary shock was observed by Wind at 1250 UT on day 40 (40/1250 UT) and was followed by a magnetic cloud arriving at 41/~0300 UT, which represents the interplanetary counterpart of the CME driving this interplanetary shock. We refer to *Cane et al*. [1998] and *Torsti et al*. [1998] for a detailed analysis of this particle event at 1 AU and to *Gopalswamy et al*. [1998] and *Webb et al*. [2000] for a detailed analysis of the solar event and its effects on the Earth environment. We point out that in contrast to SOHO/ERNE observations [see *Torsti et al*., 1998, Figure 1], Wind/3*DP* observations did not show any change in the particle flux above ~6 MeV, which remained at background levels throughout the duration of the particle event. This indicates that the ion channels from the SST detectors of the Wind/3*DP* instrument [*Lin et al*., 1995] are affected by a significant background.

One day before the arrival of the shock at Wind, there was an increase of the solar wind speed associated with a change in the IMF direction. Low-energy (<5 MeV) proton fluxes peaked with the arrival of this high-speed stream, but not with the arrival of the interplanetary shock. The arrival of the interplanetary shock at 1 AU at 40/1250 UT did not produce a peak of the proton flux at Wind. This suggests that the interplanetary shock was able to accelerate particles at high energies when it was close to the Sun (and able to produce this SEP event) but not when it arrived at Wind. The association of this interplanetary shock with the CME at 38/0030 UT gives an average transit speed of the shock to travel from the Sun to 1 AU of ~690 km s^{-1}. Figure 5c displays the Ulysses location, where the arrow indicates the direction of propagation of the shock driven by this CME (assuming it propagates from the site of the filament disappearance). Assuming a constant transit speed for the shock of ~690 km s^{-1} and an extension of at least ~50°, we should expect this shock to be observed by Ulysses around day 50. However, no shock was detected by this spacecraft at that time. It is worth pointing out that around the expected arrival time of this shock at Ulysses there is an enhancement of the particle flux. The efficiency of CME-driven shocks accelerating particles is supposed to decrease as these shocks move away from the Sun [*Lario et al*., 1998b]. When this shock arrived at Wind, it had already shown signs of its inefficiency for accelerating protons to MeV energies. We suggest that the particle flux enhancement observed by Ulysses was not related to the arrival of the CME-driven shock. We associate it with the arrival of a recurrent high-speed stream at Ulysses (numbered 5 in Figure 2). This increase of flux is higher than

Figure 6. (opposite) (a) Wind and (b) Ulysses observations for the April 1997 period. (c) Spatial configuration of the ecliptic plane on day 97. The arrow shows the source longitude of the CMEs occurring on day 97. Two nominal magnetic field lines (solid lines) have been plotted assuming a Parker spiral with a solar wind speed of 400 km s^{-1}. A solar wind speed of 600 km s^{-1} has been assumed for the high-speed stream (shaded region). The compression region is indicated by a black square, and the thick solid lines FS and RS show the forward and reverse shocks formed at its boundaries (dashed lines indicate its nominal connection to the Sun which is distant from the source region of the CMEs). The other two shocks FS, RS are associated with the leading edge of the high-speed number 2. See text for details.


E19
Halo
a 0.4–0.7 MeV
b 0.8–1.2 MeV
c 1.8–2.4 MeV
d 3.8–5.1 MeV
e 6.1–8.0 MeV
f 7.9–10.7 MeV
WIND/3DP
(a)
Flux (/cm²/s/sr/MeV)
V (km/s)
|B|(nT)
θ(deg)
φ(deg)
1997
E19
Halo
a 1.2–3.0 MeV
b 1.8–3.8 MeV
c 3.8–8.0 MeV
d 8.0–19.0 MeV
ULYSSES/COSPIN/LET
(b)
Flux (/cm²/s/sr/MeV)
V(km/s)
|B|(nT)
θ (deg)
φ (deg)
R=4.97 AU
HLONG=E42°
HLAT=13.26°
1997
R=5.02 AU
HLONG=E65°
HLAT=11.89°
DAY 97
(c)
FS
RS
WIND
RS
FS
Ulysses

the previous and subsequent recurrent particle onsets at Ulysses due to the high-speed streams (number 6 and 4 in Figure 2, but its proton-to-alpha ratios are now higher [*Sanderson et al*., 1999, Figure 3]. It is possible to associate the high-speed stream number 5 with the high speed-stream observed by Wind during days 39–40. Both streams have the same outward magnetic field polarity, and according to (1) (assuming $r_1 \sim 1$ AU, $\phi_1 \sim 0°$, $r_2 \sim 4.85$ AU, $\phi_2 \sim$ W5.7°, and $v_{sw} \sim 600$ km s^{-1}) a corotation delay time of ~11.5 days is expected, this corresponds to the time interval between the passage of the high-speed streams at Wind and Ulysses.

According to Figure 5c, when the shock driven by the CME at 38/0030 UT was close to the Sun, it was able to inject energetic particles on to the magnetic field line connected to Wind. At that time, Ulysses was magnetically connected to regions of the Sun far away from the point where the CME developed. No other solar events have been reported during the time interval under study (Solar-Geophysical Data, no. 636, 1997; LASCO's CME list on ftp://lasco6.nascom.nasa.gov/pub/lasco/status/). Therefore the shock associated with the CME at 38/0030 UT was not able to inject particles on to the field line connected to Ulysses; nevertheless, it was able to populate those field lines around Wind, including the high-speed stream that crossed Wind around days 39–40 (shaded area in Figure 5c). Owing to the corotation effect, Ulysses established magnetic connection with these field lines around day 50, which coincides with the time when the flux enhancement was observed by Ulysses. We suggest that energetic particles accelerated by the CME-driven shock propagated along the field lines within the high-speed stream passing first through the Wind site. This high-speed stream rich in particles crossed Ulysses position some days later. The shocks associated with the interaction between fast and slow solar wind and probably formed beyond the Ulysses position might have taken the energetic particles associated with this solar event as a seed particle population to reaccelerate. That created this intense particle event observed by Ulysses but with proton-to-alpha ratios characteristic of an SEP event [*Sanderson et al*., 1999].

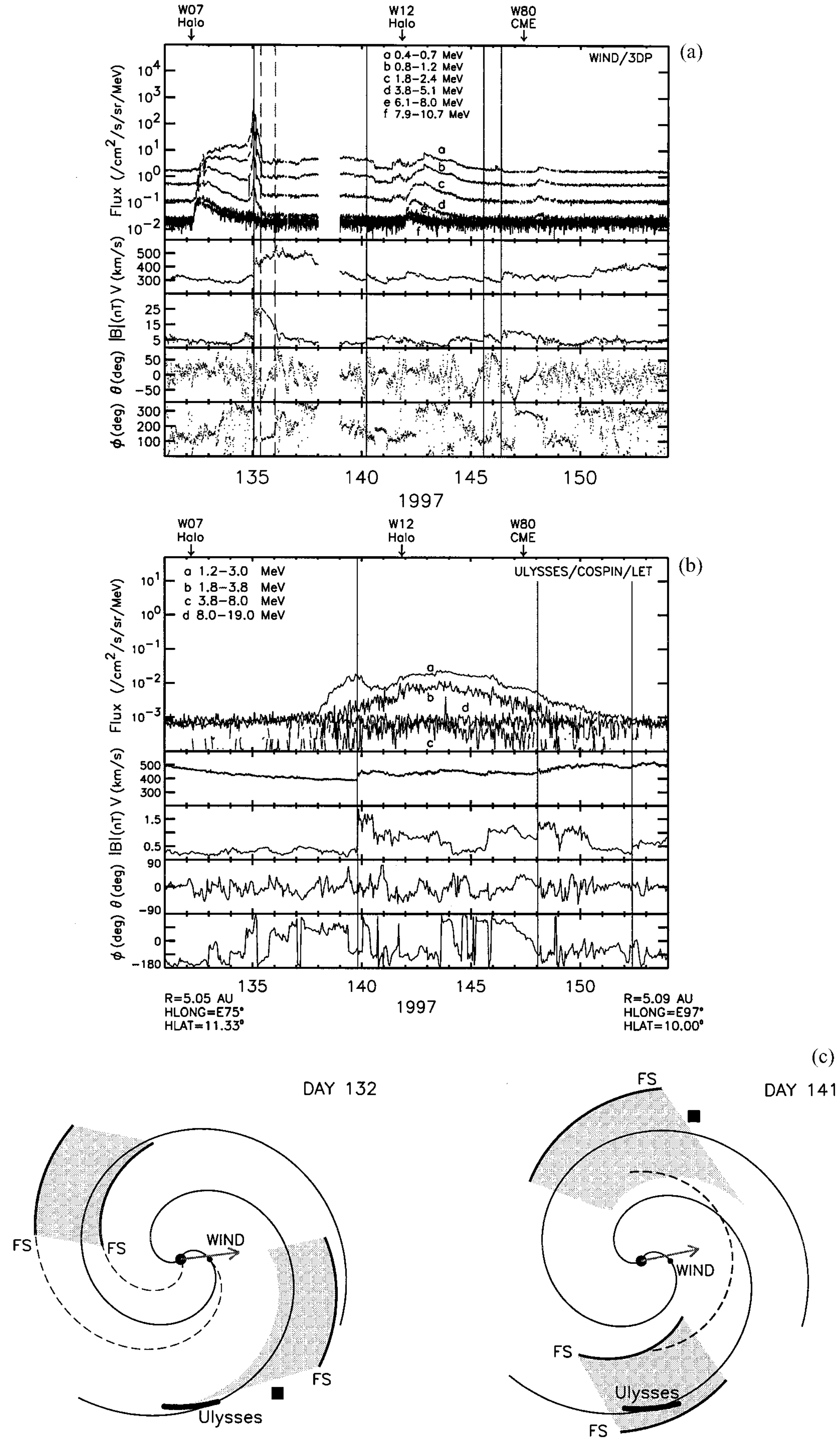
4.2. April 1997

Figure 6 shows Wind and Ulysses observations and their respective locations from day 96 to day 120 of 1997. *Berdichevsky et al*. [1998] present a detailed analysis of the SEP event observed by Wind between day 97 and 102 of 1997. This event was associated with two related ejecta from the Sun. The first was a halo CME beginning at 97/1427 UT that probably originated from the active region AR 8027 (S30°E19°) and was temporally associated with a long-duration solar flare occurring from 97/1350 UT to 97/1419 UT. A shock in the high corona driven by this CME was inferred by *Berdichevsky et al*. [1998] using type II radio burst observations. Another Earth directed halo CME was observed at 97/~1500 UT, which was associated with the interplanetary shock observed by Wind at 100/1255 UT (average shock transit speed ~590 km s^{-1}). From 101/0550 UT to 101/~1500 UT a structure identified as an ejecta (but lacking the rotation in the IMF direction characteristic of magnetic cloud) crossed Wind. This was interpreted by *Berdichevsky et al*. [1998] as the interplanetary counterpart of this second CME. During the passage of this structure an abrupt decrease of the particle flux was observed. At the shock passage a brief increase in the intensity of low-energy ($\lesssim$3 MeV) protons was observed, which indicates that the shock was still able to accelerate particles to MeV energies when it was at 1 AU. *Torsti et al*. [1998] and *Cane et al*. [1998] studied the SOHO/ERNE and IMP 8 observations, respectively, and associated the origin of the SEP event with the solar events occurring from AR 8027. We refer to the aforementioned works for a detailed analysis of 1 AU observations of this SEP event.

Proton intensities at Ulysses show a small enhancement at low energies (<3.8 MeV) around day 106, which lasts until day 119. A forward shock (FS) and a reverse shock (RS) arrived at Ulysses at 101/0721 UT and 107/1258 UT, respectively, with a relatively high IMF magnitude between them. A similar magnetic structure was identified between days 74 and 80 (but without clear shocks as boundaries) and between days 125 and 129. These two periods, identified by a black square in Figure 2e, did not show any significant increase of proton fluxes which remained at background levels in all energy channels. However, the reverse shock at 107/1258 UT had a clear contribution to the low-energy (<3.8 MeV) proton flux (Figure 6). Another forward-reverse shock pair was observed at 115/1025 UT and 118/1946 UT, with a high IMF magnitude between them. This magnetic structure was also observed with a significant increase of low-energy proton flux in the previous solar rotation between days 88 and 92 (Figure 2). This forward-reverse shock pair was associated with the compression region at the leading edge of the high-speed streams number 3 and 2 in Figure 2. The particle flux enhancement associated with the forward-reverse shock pair of the high-speed stream number 2 showed a higher intensity than for the high-speed stream number 3.

Figure 6c shows the heliospheric configuration on day 97 when the CMEs that produced the SEP event at Wind occurred; the arrow indicates the propagation direction of the shock associated with these CMEs. In principle, there was no direct magnetic connection between the Ulysses spacecraft and the source region producing these CMEs. According to Solar-Geophysical Data (no. 638, 1997) and Boulder Preliminary Reports (no. 1128, 1997), there was no evidence of solar events occurring in the nonvisible part of the Sun during this period. Therefore it is not possible to associate the particle events at Ulysses with specific solar events. Note that the maxima of the proton intensity occurred around the arrival at Ulysses of the shocks associated with corotating structures. The two shaded regions of the Figure 6c at the east and west of the Sun (as seen from Wind) are sketches of the compression region (bounded by forward and reverse shocks) arriving at Ulysses between days 101 and 107 (black square), and the high-speed stream number 2, respectively. Forward and reverse shock pairs have been schematically represented by thick solid lines. We have

Figure 7. (opposite) (a) Wind and (b) Ulysses observations for the May 1997 period. (c) Spatial configuration of the ecliptic plane (left) on day 132 and (right) on day 141. Nominal magnetic field lines (solid lines) have been plotted assuming a Parker spiral with a solar wind speed of 400 km s^{-1}. A solar wind speed of 500 km s^{-1} has been assumed for the corotating compression regions (shaded regions). The two forward shocks (FS) at the leading edge are a representation of the shocks observed by Ulysses at 139/1932 UT and 148/0128 UT. Black square indicates the compression region where the maximum of the solar wind was observed, bounded by a forward shock (FS) arriving at Ulysses at 152/0846 UT. The arrow shows the source longitude of the CME (left) at 132/0630 UT and (right) at 141/2015 UT, and the dashed semicircle (right panel) the shock driven by the first CME.


W07
Halo
W12
Halo
W80
CME
(a)
WIND/3DP
a 0.4–0.7 MeV
b 0.8–1.2 MeV
c 1.8–2.4 MeV
d 3.8–5.1 MeV
e 6.1–8.0 MeV
f 7.9–10.7 MeV
Flux (/cm²/s/sr/MeV)
V (km/s)
|B| (nT)
θ (deg)
φ (deg)
135 140 145 150
1997
(b)
ULYSSES/COSPIN/LET
a 1.2–3.0 MeV
b 1.8–3.8 MeV
c 3.8–8.0 MeV
d 8.0–19.0 MeV
R=5.05 AU
HLONG=E75°
HLAT=11.33°
R=5.09 AU
HLONG=E97°
HLAT=10.00°
(c)
DAY 132
FS
FS
WIND
FS
Ulysses
DAY 141
FS
WIND
FS
Ulysses
FS

considered that the compression regions are formed in the outer heliosphere. Assuming a solar wind speed of ~570 km s^{-1} for the high-speed stream number 2 (as observed by Ulysses on day 119), the solar source of this solar wind was at the heliolongitude of ~E160° at the time of the CMEs on day 97 (assuming a solar rotation of 13.5°/day). Therefore it was not possible that the CMEs filled directly this high-speed stream with energetic particles, as Ulysses observations on day 119 suggest. These energetic particles propagated along the field lines located around Wind. We suggest that they filled the region of the heliosphere included between the reverse shock arriving at Ulysses at 107/1258 UT and the compression region of the high-speed stream number 2 bounded by the FS-RS shock pair arriving at Ulysses at 115/1025 UT and 118/1946 UT. These shocks produced local reacceleration of these particles. Note that in the interval between RS at 107/1258 UT and FS at 115/1025 UT there was a significant flux of low-energy particles at Ulysses, but it was lower than at the arrival of the shocks. In contrast to the February 1997 events the high-speed stream number 2 was not directly filled with particles accelerated by the CMEs occurring at the Sun, and only particles locally reaccelerated at the corotating shocks were observed.

4.3. May 1997

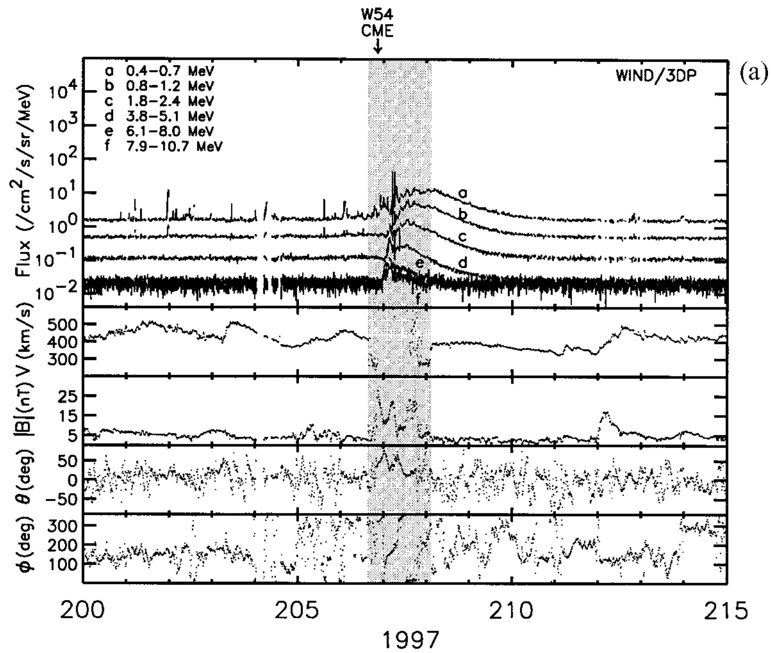
Figure 7 shows Wind and Ulysses observations together with their respective locations from day 131 to day 153. Wind observed two SEP events on days 132–136 and days 142–143 and a small particle flux enhancement on days 147–148. *Cane et al*. [1998] analyzed in detail the first two SEP events using particle observations from IMP 8 and magnetic field and solar wind observations from the Wind spacecraft. They associated the first SEP event with a halo CME observed at 132/0630 UT. *Torsti et al*. [1998] reported that the first 24–48 MeV protons were observed by SOHO/ERNE instrumentation 1.5 hours earlier than the CME occurrence. There was also a gradual solar flare from AR 8038 (N21°W07°) and a Moreton wave starting from the same point at 132/~0455 UT [*Torsti et al*., 1998]. An interplanetary shock arrived at Wind at 135/0120 UT (the association with the CME gives an average shock transit speed of ~610 km s^{-1}) and 8 hours later a magnetic cloud arrived. The arrival of the shock was accompanied by an increase of the proton flux below ~6 MeV, which represented a population of particles trapped around the shock front or locally accelerated by the shock.

The origin of the second SEP event observed by Wind was a halo CME occurring at 141/~2100 UT and temporally associated with a solar flare from AR 8040 (N05°W12°) occurring at 141/2015 UT [*Cane et al*., 1998]. A weak interplanetary shock arrived at Wind at 145/1350 UT (average shock transit speed of ~380 km s^{-1}), but no clear solar wind ejecta signatures were observed. *Cane et al*. [1998] inferred a possible small-scale ejecta structure from particle data, but it was probably not related to this transient event. Finally, there was a very small particle flux enhancement between days 147 and 148 that was probably associated with the only solar event that took place on those days, a small CME occurring at 147/1015 UT and temporally associated with a solar flare from AR 8045 (N02°W80°) at 147/0957 UT (Solar-Geophysical Data, no. 634, 1997; SOHO/LASCO observations on ftp://lasco6.nascom.nasa.gov/pub/lasco/status/). We note that there was also a change in the magnetic field orientation in association with this particle flux increase.

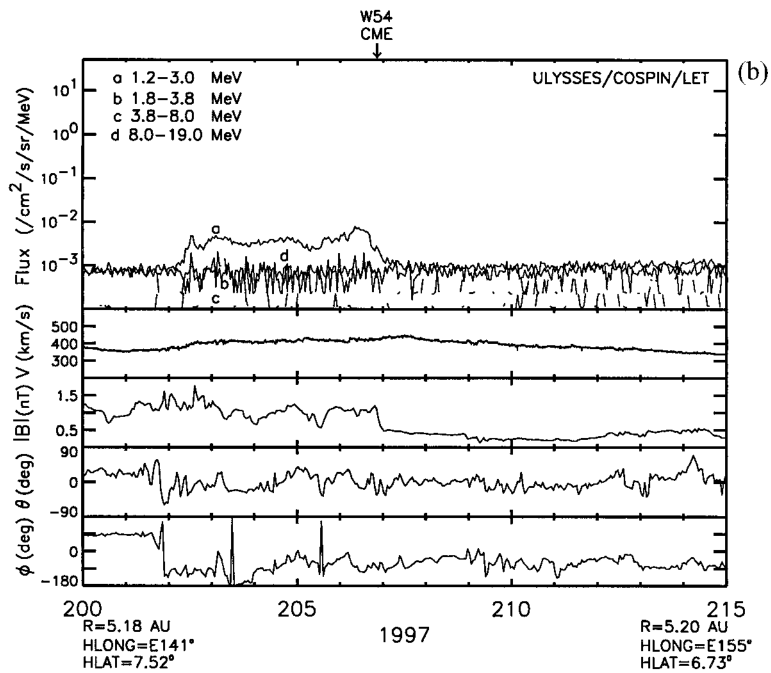
Ulysses/LET instrument observed a low-energy (<8 MeV) proton flux enhancement from day 138 to day 149. Two forward shocks were observed at 139/1923 UT and 148/0128 UT. The first was very effective in accelerating protons to low energies as clearly shown by the peak of 1.2–3.0 MeV proton flux around its passage. The origin of this shock is not related to the CME at 132/0630 UT because it would have to propagate faster in the direction to Ulysses than in the direction to Wind. There are no indications that under similar background solar wind conditions a shock originated near the Central Meridian propagates faster to the east than to the Earth. Figure 7c (left) shows Wind and Ulysses location on day 132, the large arrow indicates the direction of propagation of the shock associated with the CME at 132/0630 UT. The most probable origin for the interplanetary shock at 139/1923 UT is related to the arrival at Ulysses of the leading edge of the high-speed stream number 1 (Figure 2). Two other forward shocks of similar characteristics were observed at Ulysses at 88/1515 UT and 115/1025 UT associated with the arrival of the streams number 3 and 2, respectively (Figure 2). The shock at 139/1923 UT shows the smallest magnetic field jump discontinuity of the three shocks associated with the high-speed streams number 3, 2, and 1, but it shows the highest 1.2–3.0 MeV proton intensity. It is important to realize, however, that the leading edge of the high-speed stream number 1 shows a more irregular shape of the solar wind and magnetic field profiles than the leading edges of the high-speed streams in previous rotations (Figure 2). There is a second maximum in the magnetic field magnitude around days 145–149 with a forward shock at 148/0128 UT. A first maximum of the solar wind speed (500 km s^{-1}) arrives at Ulysses on day 150. The solar wind speed shows another increase with a maximum of ~530 km s^{-1} on day 156 in association with the compression region indicated by the black square in the Figure 2e and bounded by a forward shock at 152/0846 UT. The arrival of this shock does not produce an increase of the particle flux. The bulk of the particles arrive between the two first forward shocks at 139/1932 UT and 148/0128 UT.

We suggest that energetic particles accelerated by the shock driven by the CME on day 132 propagated along the magnetic field lines located around Wind, producing the first SEP event observed by this spacecraft from day 132 to day ~136. Shaded region in Figure 7c sketches the corotating compression region observed at the leading edge of the high-speed stream number 1, where two shocks (FS) have been plotted as thick solid lines. These two shocks correspond to the two forward shocks arriving at Ulysses at 139/1923 UT and 148/0128 UT. Assuming a solar wind speed of ~500 km s^{-1} for the high-speed number 1, the solar source of the solar wind observed by Ulysses on day 150 was at the heliolongitude of ~E94° on day ~132. The CME at 132/0630 UT occurred from W07° and probably was unable to fill this speed stream. However, the nominal magnetic connection to the compression region at the leading edge of this high-speed stream was established around the field line connecting to Wind (dashed lines in Figure 7c, left). Solar

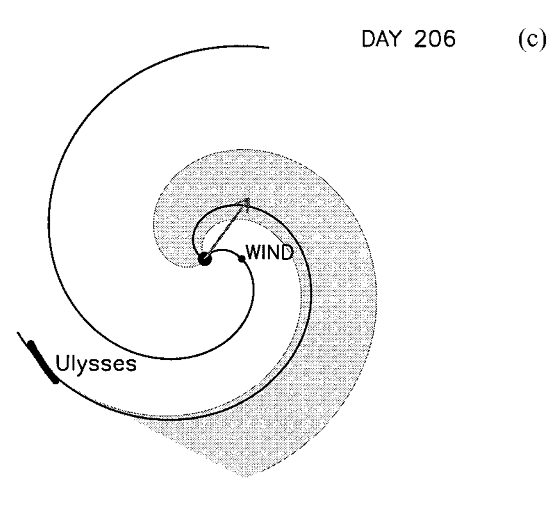
Figure 8. (opposite) (a) Wind and (b) Ulysses observations for the July 1997 period. (c) Spatial configuration of the ecliptic plane on day 206. Nominal magnetic field lines (solid lines) have been plotted assuming a Parker spiral with a solar wind speed of 400 km s^{-1}. A solar wind speed of 450 km s^{-1} has been assumed for the high-speed stream (shaded region). The arrow shows the source longitude of the CME at 206/2102 UT.



W54
CME
(a)
a 0.4–0.7 MeV
b 0.8–1.2 MeV
c 1.8–2.4 MeV
d 3.8–5.1 MeV
e 6.1–8.0 MeV
f 7.9–10.7 MeV
WIND/3DP
Flux (/cm²/s/sr/MeV)
V (km/s)
|B| (nT)
θ (deg)
φ (deg)
200
205
210
215
1997



W54
CME
(b)
a 1.2–3.0 MeV
b 1.8–3.8 MeV
c 3.8–8.0 MeV
d 8.0–19.0 MeV
ULYSSES/COSPIN/LET
Flux (/cm²/s/sr/MeV)
V (km/s)
|B| (nT)
θ (deg)
φ (deg)
200
205
210
215
1997
R=5.18 AU
HLONG=E141°
HLAT=7.52°
R=5.20 AU
HLONG=E155°
HLAT=6.73°



DAY 206
(c)
WIND
Ulysses

energetic particles propagating along this line and associated with the solar event on day 132 gained access to this compression region where they underwent reacceleration processes by the two forward shocks. The direct contribution from the CME gave to the particle flux enhancement at Ulysses the values of proton-to-alpha ratios characteristic of a transient particle event [*Sanderson et al*., 1999, Figure 3]. The black square in Figure 7c (left) identifies the other compression region that was observed after the high-speed stream number 2 and which crossed Ulysses between days 125 and 130 and crossed again between days 152 and 156 (Figure 2). Its nominal magnetic connection to the Sun was far away from the source region of the CME at 132/0630 UT.

Figure 7c (right) shows a sketch of the ecliptic plane on day 141 when the second halo CME took place (the arrow indicates the propagation direction of the associated shock), and the interplanetary shock associated with the CME at 132/0630 UT extended up to ~3 AU (dashed line). The shock front has been plotted assuming a constant speed of 610 km s^{-1} and a width of 180° centered around W07°. Distortion of interplanetary magnetic field lines in the downstream region of the shock has not been considered. The second CME had a small contribution to the proton flux at Wind (Figure 7a), and we do not expect that it had a big effect on the particle flux at Ulysses. In fact, energetic particles injected from this small solar event may have access to the reacceleration processes of the compression region shocks, but their arrival at Ulysses did not produce a significant particle flux increase.

4.4. July 1997

Figure 8 shows Wind and Ulysses observations and their respective locations during July 1997. There is a small SEP event observed by Wind at the end of day 206 with decaying phase until the middle of day 208. Ulysses observed an irregular low-energy (<3 MeV) proton flux enhancement between days 202 and 207. The fact that Ulysses did not observe any flux enhancement after the occurrence of the SEP event at Wind suggest a different scenario for this event.

The SEP event observed by Wind occurred while this spacecraft was inside the Earth's magnetosphere (shading bar in Figure 8a). *Bothmer et al*. [1997] analyze particle data from the SOHO spacecraft during the same period and associate the origin of this SEP event with a CME occurring at 206/2102 UT and propagating away from the west limb of the Sun. A long-duration solar flare occurred at 206/2035 UT from AR 8065 (N16°W54°). No signatures of interplanetary shock or ejecta were observed by Wind. The short intensity and duration of this particle event (also shown in SOHO data located outside the magnetosphere) are indicators of the limited number of magnetic field lines with SEPs propagating along them that may be due to the action of an inefficient and narrow CME-driven shock. Therefore there is a scarce possibility that this SEP event was observed at 4 or 5 AU as Ulysses observations show.

The proton flux enhancement at Ulysses was the least intense of the four proton events studied in this paper and was only observed below 3 MeV. This increase coincided with the arrival of a small high-speed (>450 km s^{-1}) solar wind stream at Ulysses and a crossing of this spacecraft with the heliospheric current sheet [*Sanderson et al*., 1999, Figure 3]. We attribute this particle flux increase to the compression region associated with this high-speed stream and also to the control established by the close presence of the current sheet (see *Sanderson et al*. [1999] for similar examples throughout the Ulysses mission). The effects of the CME at 206/2102 UT were not observed by Ulysses; the arrow in Figure 8c shows the source region of this CME. The shock driven by this CME did not accelerate particles to MeV energies at 1 AU and, in principle, we do not expect that it was able to inject particles on to the magnetic field line connected to Ulysses. Probable origin of the energetic particles observed by Ulysses lies in the processes of acceleration and injection of particles associated with corotating shocks formed beyond Ulysses location but in any case with the SEP observed by Wind.

5. Summary and Conclusions

We have presented energetic proton observations by the Wind and Ulysses spacecraft throughout 1997 and 1998. Heliospheric conditions sampled by Ulysses can be organized into two epochs that we have called period 1 and period 2. In period 1, Ulysses was moving from regions dominated by fast solar wind to slow solar wind and several recurrent high-speed streams were observed; this period was characterized by a low level of solar activity and only isolated SEP events were observed at 1 AU. Proton flux increases observed by Ulysses during period 1 were related to the arrival of recurrent compression regions associated with high-speed streams and magnetic field structures. In period 2, Ulysses was fully immersed in the slow solar wind flow; the proton flux observed by Ulysses showed a higher particle intensity, especially at high energies that reflected the increasing level of activity at the Sun. At low energies the proton flux remained at a very high level that was sustained by successive injections of particles from solar events and related shocks.

Proton flux enhancements were observed in a close temporal association at 1 AU and ~5 AU throughout 1997 and 1998, even when Wind and Ulysses were quite separated in heliocentric and heliolongitudinal distance. In broad terms, there was a similarity between Wind and Ulysses flux profiles, although a closer inspection reveals that mechanisms under which the energetic particles reached Ulysses and Wind were quite different. A first examination of the time delays between proton flux peaks at Wind and Ulysses showed a difference between period 1 and 2. In period 1 the time delay between proton flux enhancements at Wind and at Ulysses is longer than in period 2. For the four SEP events observed by Wind throughout period 1, Ulysses was always poorly connected to the CME source region. The mechanism under which the particle flux enhancements were also observed at Ulysses is the corotation of the magnetic field lines along which energetic particles propagated. The increasing level of solar activity in period 2 results in a large number of CMEs coming from different longitudes relative to Ulysses. The occurrence of several CMEs, some of them occurring in a sequence for short periods of time and some of them driving wide interplanetary shocks, resulted in filling broad regions of the heliosphere with energetic particles, and hence the observation of particle events at Wind and Ulysses in a closer temporal association and shorter time delays (see paper 2).

Detailed analysis of the particle flux enhancements throughout period 1 shows that at 1 AU there was a direct correspondence between large CMEs and SEP events [*Cane et al*., 1998]. At 5 AU the proton enhancements were associated with corotating structures. We suggest possible scenarios to explain the observation of SEP events at 1 AU together with slightly delayed particle events at ~5 AU. Energetic particles associated with the solar events (and the related shocks) were able to populate those field lines to which Ulysses established magnetic connection some days later. The shocks associated with the compression regions at the leading edge of the recurrent high-speed streams contributed to the proton flux by reaccelerating those particles. When the injection of SEPs occurred directly on to the field lines within a high-speed stream (February 1997) or connected to a compression region crossing Ulysses (May 1997), an intense particle event was observed by this spacecraft with high proton-to-alpha ratios characteristic of SEP events [*Sanderson et al*., 1999]. When SEPs were not able to fill directly the corotating compression regions but had relatively easy access to their boundary shocks (April 1997), a small particle event was observed at Ulysses and only associated with local reacceleration of particles at the shocks. In this case, the proton-to-alpha ratios were not characteristic of an SEP event [*Sanderson et al*., 1999]. When SEPs were not able to populate those field lines crossing Ulysses within a reasonable time scale, there was no associated particle event at Ulysses (July 1997). Consistent with this scenario, we suggest that SEPs contribute substantially to the seed particle population available to be accelerated by CIR-associated shocks. It is necessary, however, that solar events and CME-driven shocks are able to populate the regions of the outer heliosphere where the CIR shocks are also present. This working hypothesis could be confirmed (or rejected) by analyzing the relative abundances of different elements at 5 AU and compared with observations at 1 AU. A future Wind–Ulysses study of abundances might help to have an answer.

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