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# Observation of decay phases of solar energetic particle events at 1 and 5 AU from the Sun

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[1] The slow decay phase of gradual solar energetic particle (SEP) events has been interpreted as an indication of particle reservoirs being established in the inner heliosphere. The same phenomenon is sometimes termed spectral invariance and explained in terms of a magnetic bottle effect, whereby a barrier impedes particle escape. In alternative to the above picture, decay-phase SEPs have been ascribed to (1) continuous acceleration at an interplanetary shock front, (2) interplanetary scattering, or (3) leakage from the solar atmosphere over several days. In this paper we investigate two large gradual SEP events characterized by comparable signatures at 1 AU from the Sun. We use measurements at 1 AU made by the ACE and IMP8 spacecraft, and at 5.2 AU by the Ulysses spacecraft. At 5.2 AU, the ~MeV proton intensities during the decay phase of the two events are found to have strikingly different profiles, showing in one case a long-duration smooth decay and in the other a depletion in particle intensity. We discuss how the four above mentioned models on the origin of decay-phase SEPs would interpret the observations. *INDEX TERMS:* 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles (2114); 7807 Space Plasma Physics: Charged particle motion and acceleration; 7513 Solar Physics, Astrophysics, and Astronomy: Coronal mass ejections; *KEYWORDS:* solar energetic particles, gradual events, particle acceleration, interplanetary, propogation, reservoir

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## 1. Introduction

[2] Solar energetic particle (SEP) events, i.e., energetic particle enhancements associated with energy release events in the solar atmosphere, have been measured by spacecraft detectors for more than 30 years. A subset of these events are characterized by long duration (of the order of several days at Earth orbit) and by a very wide longitudinal extent, in the sense that their signature can be seen by spacecraft located at large longitudinal separation in interplanetary space. These are the so-called gradual SEP events, which have been reported to have a low electron to proton ratio, as well as heavy ion abundances and ionization states typical of the high corona [*Reames*, 1999]. The interpretation favored by most researchers at present is that the particles of gradual SEP events are accelerated by the shock driven by a Coronal Mass Ejection (CME) as it propagates through the corona and interplanetary space [*Reames*, 1999].

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[3] Gradual SEP events can last for many days at Earth orbit and are typically characterized by a slow quasi-exponential decay. Do we understand the reason for the presence of SEPs in interplanetary space many days after the associated solar events?

[4] Within the CME acceleration paradigm, the long duration of gradual events was initially interpreted as the result of continuous acceleration by the CME shock as it travels through interplanetary space [*Reames et al.*, 1996]. Within this picture the CME shock is still an efficient particle accelerator even at large distances from the Sun.

[5] Multispacecraft observations show that during the decay phase of many gradual events, particle intensities at spacecraft widely separated in longitude are remarkably close in absolute value and their decline in time is characterized by very similar time constants. This fact was first observed by *McKibben* [1972] and later confirmed many times. *Reames et al.* [1997] showed that the similarity in proton intensity profiles at different spacecraft is seen at all energies between 1 and ~35 MeV, and described it as spatial and temporal invariance in particle spectra. The same property was reported for electrons

[*Daibog et al.*, 2000, 2001] and for heavy ions [*Maclennan et al.*, 2001].

[6] At proton energies between 0.3 and 0.5 MeV, *Roelof et al.* [1992] compared the decay phases of large gradual events at 1 and 2.5 AU from the Sun. They identified periods when the particle intensities at the two locations were essentially the same, and described this as a zero gradient between the two locations. They suggested that these observations can be explained by the inner heliosphere acting as a reservoir at these times, as the escape of low-energy particles is impeded by large scale magnetic structures in interplanetary space. *Reames et al.* [1997] reached a similar conclusion in their analysis of the spatial invariance of particle profiles: they describe a magnetic bottle effect whereby "particles are quasi-trapped in the region behind the shock accelerating them, experiencing intense scattering at the shock and mirroring in the converging fields near the Sun."

[7] Prior to the establishment of the CME acceleration paradigm, the long duration of gradual events used to be interpreted purely as the result of particle scattering in interplanetary space. By fitting SEP time profiles with scattering models many workers reached the conclusion that the particle mean free path is of the order of 0.1 AU [e.g., *Kallenrode*, 1993a, and references therein]. The establishment of the CME acceleration paradigm however has produced a shift in perspective whereby the role of scattering is thought to be minimal [see *Reames*, 1999, p. 470], also following reports that the scattering mean free path is much larger than previously estimated [*Mason et al.*, 1989]. It should be noted however that models of acceleration at interplanetary shocks require values of the scattering mean free path of the order of 0.1 AU [*Kallenrode and Wibberenz*, 1997; *Lario et al.*, 1998]. An alternative explanation for the long decay phase of gradual events is that of extended leakage of energetic particles from the solar atmosphere. This idea was reproposed by *Simnett* [1996] after having been the accepted theory for many years in the sixties and seventies.

[8] In this paper we compare the decay phases of two large gradual SEP events observed at 1 AU from the Sun by the ACE and IMP8 spacecraft, and at 5 AU by the Ulysses spacecraft. The two events were selected because they have comparable intensity profiles at both 1 and 5 AU for proton energies in the range 30–100 MeV. While comparable profiles are seen also at energies of a few MeVs at 1 AU, the profiles at 5 AU in this range are very different, showing in one case a smooth long-duration (~30 day) event, and in the second one a depletion in flux for a duration of ~12 days. A preliminary discussion of the two events was given by *Dalla et al.* [2001a].

[9] We test possible interpretations of the decay phase of gradual events against this data. We consider how the depletion at ~1 MeV at Ulysses would be interpreted by four models of decay-phase energetic particles: continuous shock acceleration, reservoir model, interplanetary scattering, and extended release from the solar atmosphere. The measurements at 1 and 5 AU are presented in section 2, and the discussion and conclusions in section 3.

## 2. Observations

[10] Two large SEP events were detected by spacecraft following solar events which took place on 24 August 1998 and 20 January 1999. On both days intense (X1.0 and M5.2 respectively) long-duration flares were observed, and a halo CME was reported for the second date by the Mauna Loa Solar observatory, with no SOHO observations available for either event. The timing and characteristics of the solar events were discussed by *Dalla et al.* [2001b].

### 2.1. SEP Observations at 1 and 5 AU

[11] Figure 1 shows hourly averages of SEP fluxes and local solar wind parameters for the events on 24 August 1998 (Figure 1a) and 20 January 1999 (Figure 1b), at a distance of 1 AU from the Sun. The data are from instruments on board the ACE and IMP8 spacecraft. Particle fluxes displayed are of protons in the energy ranges 1.9–5 and 30–95 MeV, and of electrons in the range 6–12 MeV. In the remainder of the paper we will refer to protons of energy around 1 or 2 MeV as "low energy" and protons above 30 MeV as "high energy." Data displayed in each panel cover 38 days.

[12] In both cases the solar event was sufficiently energetic to produce relativistic electrons and high-energy protons, as can be seen from the bottom and middle plots in the top panels of Figure 1 (data gaps are present in the IMP8/CRNC channels at the start of both events). The solar wind and magnetic field data show the arrival of a shock 32 hours after the flare onset in August 1998 and after 48 hours in January 1999. The fluxes of 1.9–5 MeV protons show a large increase in correspondence with both shock passages. Local shock acceleration can be seen also at higher energies, less clearly for the January 1999 event. The two events are of long duration, of approximately 7 days in the relativistic electron channel. The durations at the different energies are similar in the two cases.

[13] Figure 2 shows the measurements made by the Ulysses spacecraft at ~5.2 AU from the Sun and close to the ecliptic plane, during the same time periods as in Figure 1. In both panels large flux enhancements are seen for protons of energies from the 1.3–2.2 MeV range (COSPIN-ATs channel) to the 38–125 MeV range (COSPIN-KET channel). Relativistic electrons are detected only for the January 1999 event.

[14] SEP events of this type are quite rare at 5 AU: in fact only four main flux enhancements were detected at Ulysses in the 38–125 MeV proton channel during the whole of 1998 and 1999. These data show a statistically significant recurrence every ~140 days [*Dalla et al.*, 2001b]. The events of 24 August 1998 and 20 January 1999 are part of the recurrent sequence.

[15] Measurements at 1 and 5 AU for each of the two time periods can now be compared. Looking at Figures 1 and 2, in particular at the high-energy proton and electron traces, it seems reasonable to conclude that the 1 AU spacecraft and Ulysses are observing the same two SEP events. The longitudinal separation between the foot points of Earth and Ulysses is 96° in August 1998 and 71° in January 1999, and it is known that gradual SEP events can have large longitudinal extent.

### 2.2. Comparison Between the Two Events

[16] We can now make a comparison between the two events, by looking at panels (a) and (b) first in Figure 1 and then in Figure 2. At 1 AU the SEP profiles are similar at all

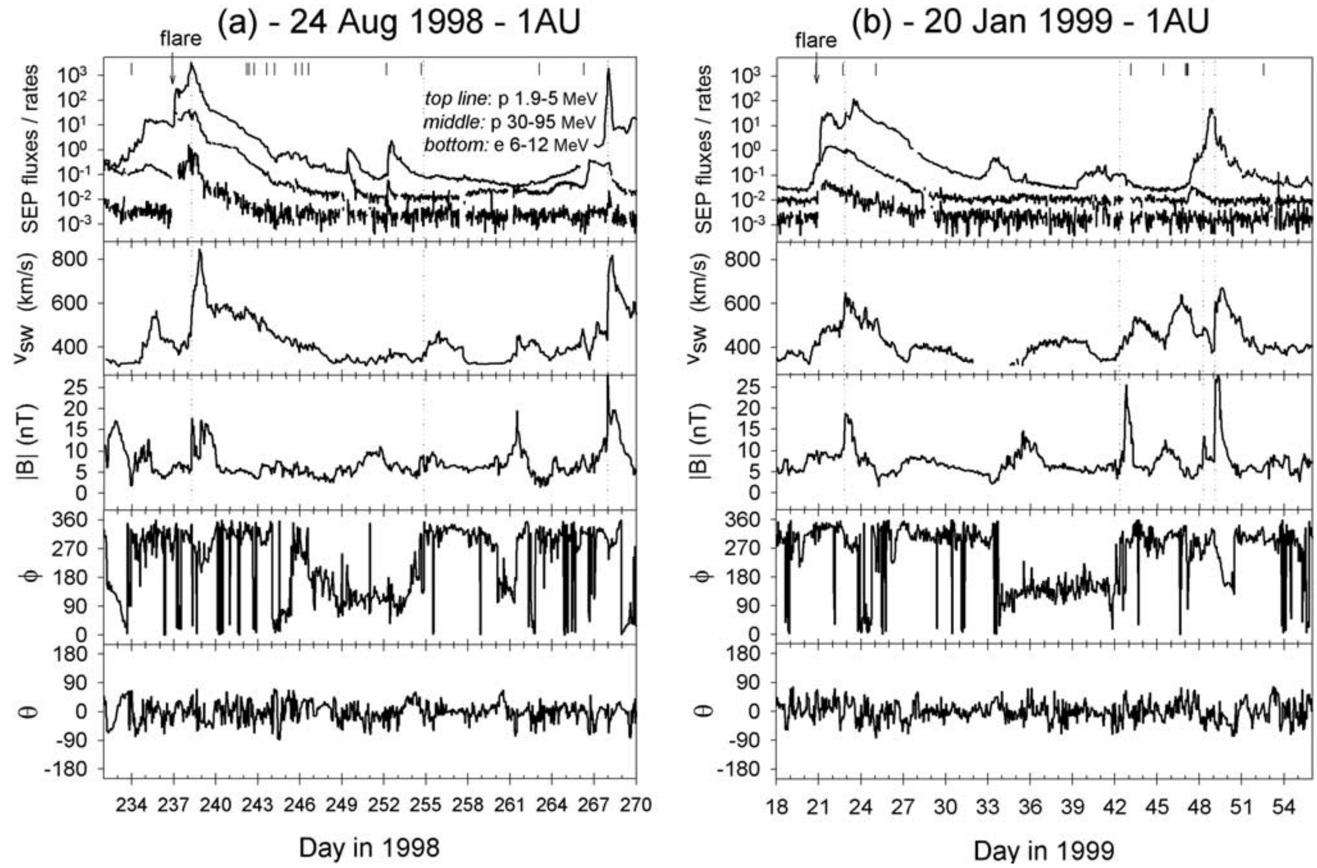


**Figure 1.** Measurements of SEPs at 1 AU from the Sun for the events on 24 August 1998 (a) and 20 January 1999 (b). The format is the same for (a) and (b), as follows. Top panel: from top to bottom curves: fluxes of 1.9–5 MeV protons (ACE/EPAM); count rates of 30–95 MeV protons (IMP8/CRNC) and of 6–12 MeV electrons (IMP8/CRNC). Second panel: solar wind speed (ACE/SWEPAM). Remaining panels: magnetic field magnitude $|B|$, meridional angle $\phi$, and azimuth $\theta$ in the RTN coordinate system (ACE/MAG). Each tick on the $x$ axis is 1 day. Particle fluxes are in (cm$^2$ s sr MeV)$^{-1}$ and count rates in s$^{-1}$. Vertical dotted lines indicate the time of passage of shocks at 1 AU, from the ACE shock list (C. Smith, personal communication, 1998). Vertical ticks in the top of the first panel are at times of GOES flares with classification M1.0 or higher. The arrow in the same panel indicates the time of the flare associated to the SEP events.

energies, with the exception of the time period around shock passage. The events' durations are comparable at all energies. At 5 AU the first similarity is that both events produce high-energy protons, a rare occurrence at this distance from the Sun. The durations of decay phases in the high-energy proton channels are similar. The onset phases of the events are very different, a fact which can be explained in terms of magnetic connection of the spacecraft to the Sun as described below. Overall, we argue that the two events on 24 August 1998 and 20 January 1999 can be regarded as "similar," in terms of their acceleration efficiency and duration at high energies.

[17] Comparing the top panels in (a) and (b) of Figure 2, however, we observe that at 5 AU the overall time intensity profiles in the 1.3–2.2 MeV proton channel are very different in the two events. In August 1998, the profile is characterized by a smooth slow decay, lasting a total of 30 days. In January 1999, a drop in intensity is seen, starting on day 26. The intensity continues to decrease until day 32, when another enhancement peaking on day 37 is seen. The flux in the 5.4–25 MeV proton channel also shows a similar profile, with the second peak less pronounced. During the time period between the two peaks the flux in the latter channel is well above background levels.

[18] We now discuss the onset phases of the events displayed in Figures 1 and 2. The locations of the Earth orbit spacecraft (E) and Ulysses (U) are given in Figure 3, where arrows indicate the longitude of the solar flare we associated with the events. The Parker spiral field lines through Earth and Ulysses are calculated using the solar wind speed measured at the start of the two SEP events. We observe from Figure 3 that the foot point of the magnetic field line through Ulysses has a smaller longitudinal separation from the flare site in the event of 20 January 1999 than for 24 August 1998. This results in a shorter risetime for the former event. The risetime at Ulysses for the 3–10 MeV electrons is ~10 hours, indicating good connection to the acceleration source. Analysis of the onset in Figure 2b shows that the risetime is also small in the ATs 1.3–2.2 MeV channel, being of ~20 hours. The time a 2 MeV

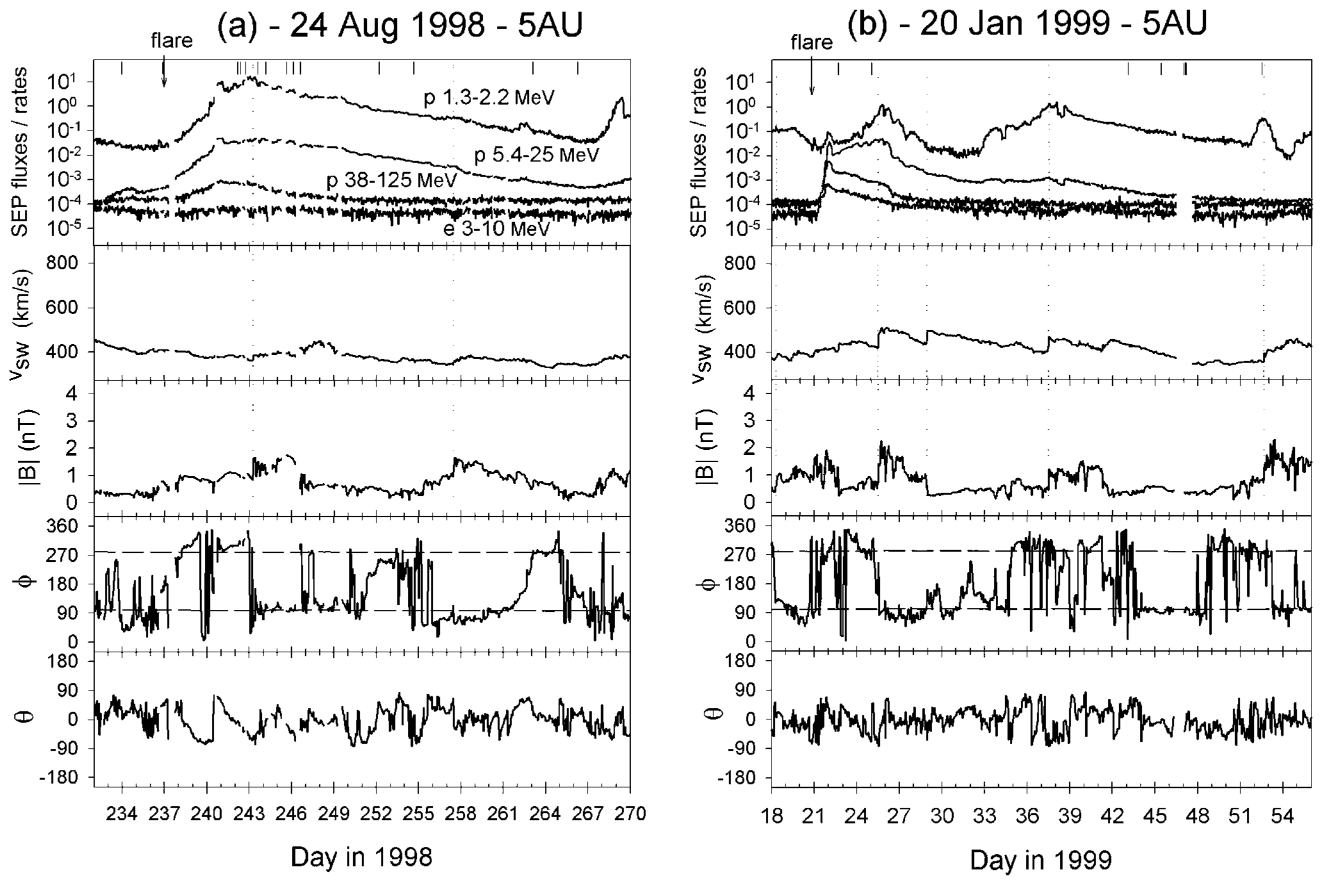


**Figure 2.** Measurements at 5 AU from Ulysses instruments, for the same time periods as in Figure 1. The format is the same for (a) and (b), as follows. Top panel: from top to bottom curves: fluxes of 1.3–2.2 MeV protons (COSPIN-ATs); fluxes of 5.4–25 MeV protons and 38–125 MeV protons (COSPIN-KET); count rates of 3–10 MeV electrons, divided by a factor 100 (COSPIN-KET). Fluxes are in $(cm^2\ s\ sr\ MeV)^{-1}$ and count rates in $s^{-1}$. Second panel: solar wind speed (SWOOPS). Remaining panels: magnetic field magnitude $|B|$, meridional angle $\phi$ and azimuth $\theta$ in the RTN coordinate system (magnetometer). In the panel for $\phi$, the dashed lines indicate the direction of a sunward (bottom dashed line) and antisunward (top dashed line) ideal Archimedean spiral calculated using the measured solar wind speed. Vertical dotted lines indicate the time of passage of shocks at Ulysses (R. J. Forsyth, personal communication, 1998). Vertical ticks in the top of the first panel are at times of GOES flares with classification M1.0 or higher. The arrow in the same panel indicates the time of the flare associated to the SEP events.

proton takes to reach Ulysses by travelling along a Parker spiral of length 14 AU can be calculated to be about 30 hours. We conclude therefore that some contamination from higher energy particles is the most likely cause of the small peak starting on day 21 in the ATs 1.3–2.2 MeV channel and possibly in the KET 5.4–25 MeV channel.

[19] The issue also arises of how the position of the two spacecraft changes during the events, in particular during

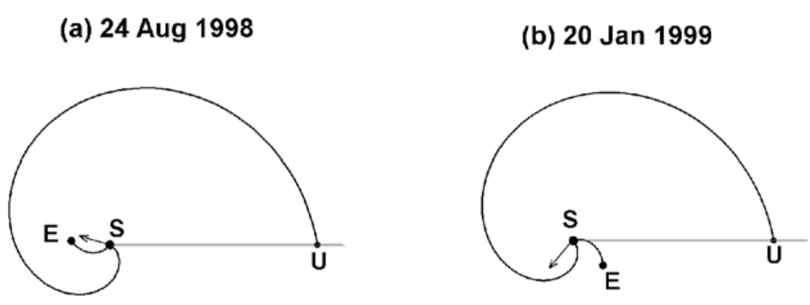


**Figure 3.** Connection of Earth orbit spacecraft and Ulysses to the Sun at the start of the two SEP events. The arrows indicate the solar longitude of flares associated to the events.

the decay phase. Because the Ulysses spacecraft is in a polar orbit around the Sun, its heliographic longitude in an inertial system changes very slowly and can be regarded as constant during the two events considered. Similarly its distance from the Sun can be regarded as constant. However, the inertial heliographic longitude of Earth and spacecraft orbiting it will change by ~30° in 30 days. Looking at Figure 3, this means that the Earth's position and its connection to the Sun will drift anticlockwise by ~30° between the onset and end of the decay phase of the events.

[20] Regarding the solar wind and magnetic measurements at Ulysses, we observe that on 24 August 1998 Ulysses and Earth were separated in longitude by 174°, and we do not expect any correlation in the local parameters at the two spacecraft. On 20 January 1999, their longitudinal separation was 40°.

### 2.3. Interpretation of 5 AU Low-Energy Profiles

[21] If one accepts that the two solar events are generally similar, the low-energy proton time profiles at 5 AU appear strikingly different. However, when the 1.3–2.2 MeV proton traces plotted in panels (a) and (b) of Figure 2 are superimposed, one can see that the timescales of the two events at this energy become very similar if one assumes that both enhancements in January 1999 are associated to a single solar event, the one on 20 January. This is also true for the 5.4–25 MeV proton trace, which in January 1999 is well above background for more than 20 days.

[22] Can we exclude that the second enhancement in 1999 is due to a separate solar event? Looking at the 1 AU 1.9–5 MeV proton data in Figure 1b, we observe that there is no enhancement at 1 AU that would correspond to the second peak at 5 AU. A small particle increase on day 32 is seen; since this takes place after intensities start increasing at 5 AU, it is most likely unrelated. A comparison between SEP data at 1 and 5 AU for the time periods considered in this paper shows that generally an event needs to have a large peak flux at 1 AU to be seen also at 5 AU.

[23] The foot points of magnetic field lines of Ulysses and Earth in January 1999 are separated by 70°. There is therefore a small possibility that the second enhancement at Ulysses might be due to a solar event to which the Earth is not well connected. Flare catalogues in Solar Geophysical Data show that, besides the flare on 20 January, the only other long-duration flare in the period displayed in Figures 1 and 2 was a C5.1 flare on day 35 of 1999, after the ~MeV flux in the ATs instrument had already started to increase. At the beginning of 1999 the Ulysses foot point was well visible from the Earth.

[24] We conclude that there is no evidence in SEP data and records of solar events that the second enhancement at low energies at 5 AU was associated to a separate solar event.

[25] It is also possible that the ~1 MeV protons part of the second enhancement at Ulysses might be of interplanetary origin, for example they could be the result of local shock acceleration. An interplanetary shock was detected at Ulysses on day 37 of 1999, its locally measured speed being 467 km/s. The possibility of local particle acceleration at this shock cannot be excluded. However, we observe that rather than being a short duration enhancement at the time of shock passage, the event has a long duration, with a decay phase lasting many days.

[26] In summary, the low-energy data in Figure 2b can be interpreted, in comparison with the Figure 2a data, according to the following two scenarios. In the first scenario comparable profiles would be expected at 1 MeV on the basis of the similarities at the higher energies in the two events; as a consequence the two peaks at 5 AU in 1999 are interpreted as a single particle event with a depletion in the middle. In the second scenario profiles at ~1 MeV do not mimic the behavior at higher energies: therefore a similarity of low-energy profiles between the two events is not expected and the cause of the second enhancement in 1999 is most likely entirely separate from that of the first enhancement.

[27] We interpret the events presented in this paper according to the former scenario. This is because it seems likelier and because there is no evidence in the data for the second enhancement in 1999 being due to a separate cause. We will call the hole in ~MeV proton intensities seen in January 1999 a depletion region, and investigate how this observation would be explained by different models of decay phases of SEP events.

### 2.4. Anisotropies at 5 AU

[28] The Ulysses ATs instrument provides anisotropies for ~MeV energy protons. The two telescopes of the ATs each collect particles into eight sectors, for a total of 16 directional flux measurements. For a channel of center energy $E$, we indicate as $J(E, \vec{e}_v)$ the measured differential flux along the direction identified by the unit vector $\vec{e}_v$, taken as pointing toward the center of the sector under consideration. We assume that the flux can be fitted by means of a reduced second-order spherical harmonic expansion as follows:

$$J(E, \vec{e}_v) = J_0(E)\left[1 + \vec{A}_1(E) \cdot \vec{e}_v + A_2(E)\frac{3\mu^2 - 1}{2}\right] \qquad (1)$$

where $\mu = \cos \Psi$ and $\Psi$ is the pitch angle of detected ions, i.e., the angle between the magnetic field and the vector $\vec{e}_v$, and we have assumed the second-order harmonics to be gyrosymmetric about the magnetic field direction, which is known from magnetometer measurements. In our analysis the units of flux are: $(\text{cm}^2 \text{ sr s MeV})^{-1}$.

[29] By substituting into the left hand side of equation (1) the measured values of the differential flux, a set of 16 equations involving the unknown coefficients $J_0$, $\vec{A}_1$ and $A_2$ is obtained. As the number of equations available is larger than the number of unknowns, we can use a least squares fit procedure to obtain the required coefficients. $J_0$ is called the omnidirectional flux, $\vec{A}_1$ the first order anisotropy vector and $A_2$ the second-order anisotropy.

[30] The ATs anisotropy coefficients for the events of 24 August 1998 and 20 January 1999 are given in Figure 4 for the 1.3–2.2 MeV proton channel. The plot gives the omnidirectional flux $J_0$, the first order anisotropy, represented by its magnitude $A_1$ and two direction angles $\phi_a$ and $\theta_a$ in the RTN coordinate system, and the second-order anisotropy $A_2$. The RTN coordinate system has the R axis along the Sun-spacecraft direction, pointing away from the Sun; the N axis is perpendicular to R in a plane containing R and the solar rotation axis, and it points northward; and T completes a right-handed coordinate system. The meri-

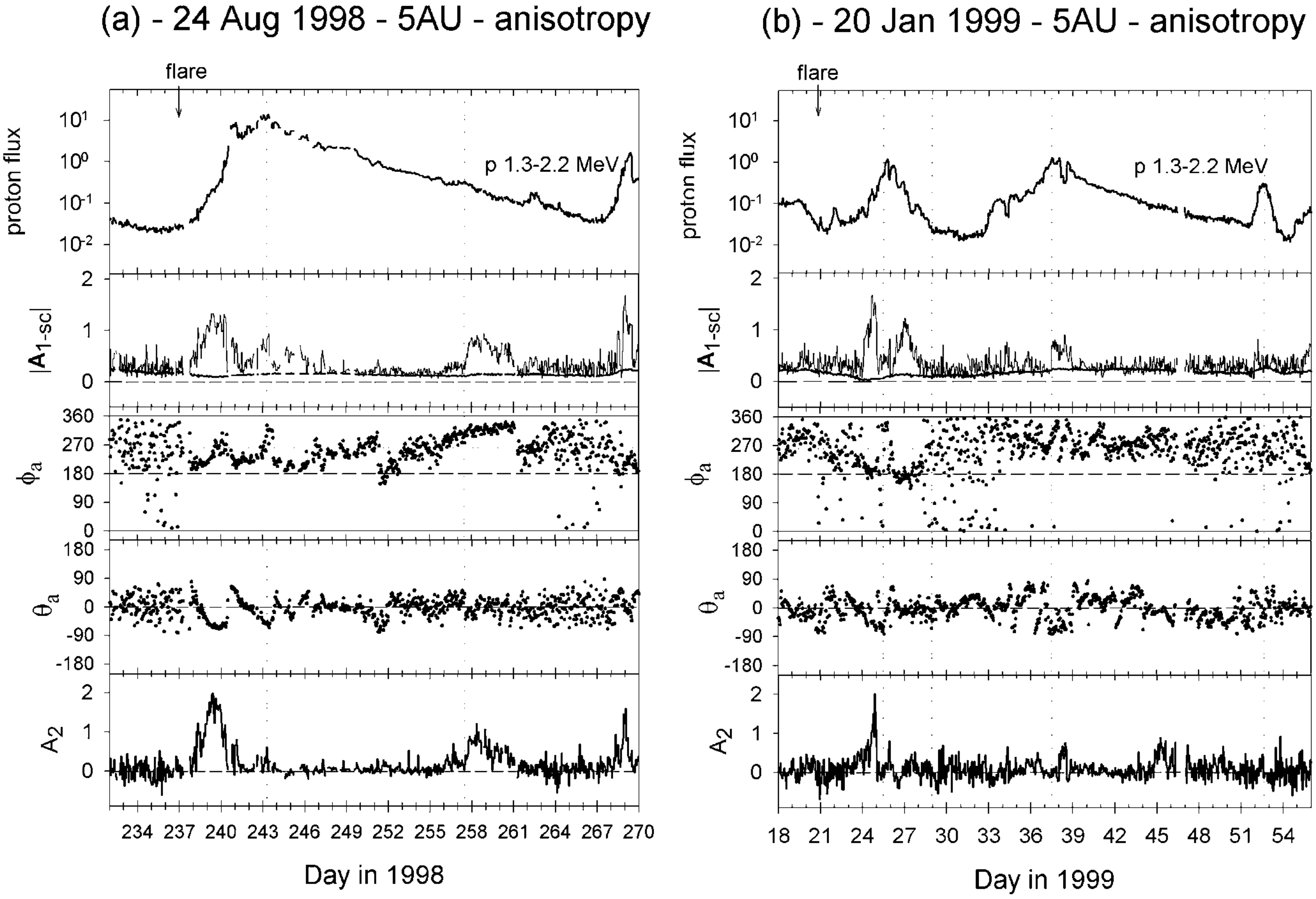


**Figure 4.** ATs anisotropy coefficients for 1.3–2.2 MeV protons. From the top panel: omni-directional flux $J_0$; magnitude of the first order anisotropy in the spacecraft frame (thin solid line) and of the calculated Compton-Getting anisotropy (thick solid line); meridional angle $\phi_a$ of the first order anisotropy vector in the RTN coordinate system; azimuthal angle $\theta_a$; second-order anisotropy $A_2$. The meridional angle $\phi_a$ is plotted with respect to the direction of a sunward ideal Archimedean spiral magnetic field line.

dional angle $\phi_a$ is plotted here with respect to the direction of a sunward ideal Archimedean spiral magnetic field line, direction calculated by using the solar wind speed measured at Ulysses. Therefore $\phi_a = 0°$ represents a particle flow toward the Sun along the ideal Archimedean spiral, and $\phi_a = 180°$ an anti-sunward flow along the spiral. The dotted horizontal line in the panel for $\phi_a$ in Figure 4 represents the radial direction pointing away from the Sun. The azimuthal angle $\theta_a$ of the anisotropy vector takes values from $-90°$ to $+90°$.

[31] The anisotropies plotted in Figure 4 are in the spacecraft frame. In interpreting these data one needs to take into account the anisotropy resulting from the solar wind being convected through the spacecraft. This is referred to as the Compton-Getting anisotropy and can be calculated to have the following expression [*Forman*, 1970]:

$$\left(\vec{A}_1\right)_{cg} = \frac{2(\gamma+1)}{v_i}\vec{V}_{sw} \tag{2}$$

where $\vec{V}_{sw}$ is the solar wind velocity, $\gamma$ is the spectral index of the ion flux energy spectrum (assuming the latter can be fitted by a curve $E^{-\gamma}$) and $v_i$ is the ion speed. The magnitude of the Compton-Getting anisotropy, calculated using equation (2) and the measured values of the solar wind speed and spectral index from the ATs spin-averaged channels, is given by the bottom line in the second panel in Figure 4. The Compton-Getting anisotropy is directed radially because the solar wind is predominantly radial.

[32] At the start of both events very large anisotropies are seen. The direction angles of the first order anisotropy vector closely follow the time variation of the direction angles of magnetic field, indicating a particle flow along the field lines. In August 1998 a magnetic cloud is observed at the start of event, starting on day 238. The high anisotropies at this time indicate strong streaming along the magnetic field direction, with the high second-order anisotropy indicating a large component of bi-directional streaming.

[33] Starting on day 247 in Figure 4a, the magnitude of the first order anisotropy decreases to a value close to the one expected from the Compton-Getting formula, and its direction becomes radial. The dotted lines in Figure 4 indicate the time of passage of interplanetary shocks at Ulysses. In panel (a), an enhancement in anisotropy is seen 2 days before the passage of a shock at 1112 UT on day 257

of 1998 (R. J. Forsyth, private communication, 1998). After shock passage an enhancement in anisotropy is seen, during which the direction angles of the anisotropy follow the time evolution of the magnetic field direction. The anisotropy direction does not show a discontinuity at the shock. During the final part of the August 1998 event the Compton-Getting anisotropy seems to underestimate the observed magnitude of the anisotropy. Another shock was observed at Ulysses at 0641 on day 243.

[34] In Figure 4b, three shocks are seen in the Ulysses data during the January 1999 event: at 1145 UT on day 25, at 2243 UT on day 28, and at 1157 UT on day 37 (R. J. Forsyth, private communication). During the time period between the arrival at Ulysses of the first two of these shocks, a large antisunward anisotropy is observed. This corresponds to the time period from the onset of the decrease in ~MeV ion fluxes to about 1 day prior to the arrival of the shock late on day 28. In the time period following the latter shock the Compton-Getting formula seems to underestimate the observed anisotropy. A significant enhancement in anisotropy is seen in Figure 4b after the passage of the shock on day 37. The direction of this anisotropy is anti-sunward.

### 2.5. Depletion Region and Solar Wind Measurements

[35] Having interpreted the two enhancements in low-energy protons seen in the January 1999 event as associated to a single solar event, we now investigate whether any changes in the solar wind speed and magnetic field happen in time coincidence with the onset or end of the depletion region.

[36] From Figure 2b, we determine that the onset of the depletion is at about 0400 UT on day 26. We observe that a decrease in particle flux is seen not only in the low-energy proton channel, but also in the KET 5.4–25 MeV and 38–125 MeV proton channels. Fluxes start increasing again in the 1.3–2.2 MeV proton channel around midday on day 32, and it is on day 37 that a slow quasi exponential decay is reestablished. We searched for temporal coincidence between these times and changes in the solar wind speed or magnetic field.

[37] The solar wind and magnetic field Ulysses data are characterized by the arrival of three shocks, as detailed in section 2.4. The first of these shocks arrives at Ulysses ~16 hours prior to the start of decrease in particle fluxes, thus not in time coincidence. There is no detectable change in intensities close to the second shock, while the arrival of the third shock, on day 37, is in time coincidence with the end of the depletion phase. There appears to be no correlation between changes in the magnetic polarity and changes in particle intensities.

[38] In summary, we do not find a direct correlation between any local solar wind parameter and either the onset of the depletion region and the time when fluxes start recovering. However, the end of the depletion region coincides with the passage of a shock at Ulysses.

[39] We then compare the general solar wind conditions we observed at 5 AU in August 1998, when no depletion was detected, and in January 1999. We observe that many more stream interaction regions are present in January 1999, when compared to the very flat solar wind speed time profile of August 1998. However, the arrival of the first stream interaction region at Ulysses precedes the onset of the depletion.

## 3. Discussion

[40] The origin of the energetic particles observed during the decay phase of SEP events is at present not well understood. At 1 AU from the Sun, gradual events can last for many days, and when observed by multiple spacecraft, can display invariant features.

[41] In sections 3.1–3.4 below we consider four possible explanations for the presence of energetic particles in the interplanetary medium days after the associated solar events. We examine how each of the theories would explain the different time profiles observed in the August 1998 and January 1999 events at low energies at Ulysses, and whether each interpretation is supported by the observations.

### 3.1. Continuous Acceleration at Shock Front

[42] Within this model, particles continue to be accelerated by a CME-driven shock even when the shock is far away from the Sun [*Reames et al.*, 1996]. After going past a spacecraft at 1 AU, for example, the shock will continue to efficiently accelerate interplanetary particles to high energies. Therefore the particles of the decay phase of an SEP event originate in interplanetary space. Their direction of arrival should reverse after the passage at the spacecraft of the accelerating shock. It has been shown that the shock acceleration efficiency generally decreases with increasing distance from the Sun [*Kallenrode and Wibberenz*, 1997].

[43] A sudden change in energetic particle intensities late in an event can occur if the detecting spacecraft becomes connected to a different (more/less efficient) portion of the shock front. For example, *Reames et al.* [1996] have interpreted some abrupt changes in particle intensities as the result of large variations in solar wind speed, causing a sudden change in connection.

[44] The August 1998 event would be interpreted within this model as resulting from good connection of Ulysses to the accelerating shock throughout the event, resulting in a smooth long-duration decay. The particle depletion observed in January 1999 would be the result of a change in the magnetic connection of the spacecraft to the shock front at which acceleration is taking place. This change could be due to: (1) a change in the geometry as the shock propagates through the heliospheric medium, so that the spacecraft is for a time no longer connected to the shock, or (2) a sudden change in the solar wind speed, so that the spacecraft is now connected to a different portion of the shock.

[45] As far as propagation of possible accelerating shocks for the two events is concerned, one can see by looking at Figure 3 that a shock centered around the longitude of the associated flare would be travelling in a direction opposite to Ulysses in August 1998, and at an angle of ~130° in January 1999. Assuming that the shocks producing the acceleration are those detected at 1 AU within 2 days of the event, their average speeds would be of 1300 and 870 km/s for August and January respectively. It does not seem likely that Ulysses could be still magnetically connected with these shocks late in the decay of the events discussed.

[46] It should be noted that, as a result of timing/speed considerations, none of the shocks detected at the Ulysses spacecraft during the August 1998 event is likely to be the same shock seen at 1 AU. Regarding the event in 1999, it is possible that the shock seen on day 37 at 5 AU might be the one observed at 1 AU on day 22. This would require the shock to have an angular extent of approximately 260° and an average speed between 1 and 5 AU of 490 km/s.

[47] Regarding the possibility of a sudden change in magnetic connection to the accelerating shock in the 1999 event, the Ulysses data shows no change in solar wind speed at the onset of the depletion region, and the end of the region is associated to an increase in solar wind speed of about 70 km/s. We observe in Figure 1 that much larger changes in the solar wind speed at 1 AU do not appear to affect the SEP time profiles significantly.

[48] In summary, an interpretation of the events discussed in this paper in terms of continuous shock acceleration seems quite difficult. The geometrical propagation of the two shocks observed at 1 AU would not be expected to produce such different intensity patterns at 5 AU, and no evidence of a sudden change in solar wind speed was seen in 1999.

### 3.2. Magnetic Bottle/Reservoir

[49] According to the magnetic bottle and reservoir interpretations, particles are still observed days after the solar event because a magnetic barrier is impeding their escape from the inner heliosphere. The barrier is thought to be the CME shock accelerating the particles [*Reames et al.*, 1997] or series of shocks from CME events preceding the solar event which accelerated the particles [*Roelof et al.*, 1992]. The reservoir particle population is a quasi-equilibrium one, displaying uniformity along the radial direction and over wide longitudinal ranges. As far as we are aware, there is no indication in the literature as to the maximum energy for which the bottle mechanism should be effective.

[50] Within the reservoir/bottle model, the depletion in particle intensities observed in January 1999 would be a result of the 3-D structure of the reservoir. Within the model, only a fraction of the magnetic flux tubes in the heliosphere are characterized by a quasi-equilibrium energetic particle population.

[51] The lack of coronograph observations for both periods makes it impossible to verify whether a series of CMEs prior to the two events might have generated shocks creating a barrier for particle propagation. The number of interplanetary shocks detected at Ulysses in the 20 days prior to the events considered is 3 in both cases.

[52] There is no indication in the solar wind parameters measured at Ulysses of a loss of connection or 3-D structure corresponding to the depletion in particles.

### 3.3. Interplanetary Scattering

[53] Within the scattering interpretation, particle release in the solar atmosphere takes place over timescales smaller than 1 day. The reason for the presence of energetic particles at 1 AU a few days after the solar event is that a fraction of particles are very efficiently scattered by the turbulent interplanetary magnetic field. They travel slowly through interplanetary space, on average. Scattering mean free paths consistent with the long duration of gradual SEP events are typically $\sim$0.1 AU, and increase slowly with increasing particle rigidity [*Beeck et al.*, 1987], though there can be significant differences from event to event [*Kallenrode*, 1993a]. A survey of mean free paths along the Ulysses orbit obtained from magnetometer observations and quasi-linear theory was presented by *Erdös et al.* [1999]. The results showed a large variability in the mean free path, mainly dependent on solar wind speed, with a weak dependence on heliocentric distance.

[54] If interplanetary scattering were the mechanism by which a particle population is sustained for long time periods, the January 1999 event would be the result of regions of very different scattering mean free path being sampled. Mean free paths would be much larger in the flux tubes associated with the particle depletion. Then a region of smaller mean free path would be traversed. This could be the case if large differences had been observed in the solar wind speed; however during the whole event the solar wind remained at low to intermediate speed as shown in Figure 2 (second panel from top). It cannot however be excluded that a variation in the scattering mean free path due to other causes might have taken place.

### 3.4. Extended Leakage From the Solar Atmosphere

[55] Within this model, some mechanism for storage in the solar corona exists, so that leakage of energetic particles from the solar atmosphere takes place over several days [*Simnett*, 1996].

[56] If the solar atmosphere were the source of the energetic particles throughout an SEP event, the depletion region in January 1999 would correspond to a loss of connection of Ulysses to the region of the Sun from where particles are leaking. This loss of connection could be due to a sudden change in solar wind speed, or to the spacecraft's connection point on the Sun crossing a boundary between a region from where particles are leaking and one where they are not. Such a natural boundary on the Sun could be the current sheet separating regions of opposite magnetic polarities.

[57] The possibility that changes in particle intensities might take place in correspondence with magnetic sector boundary crossings observed in magnetometer data was discussed by *Kallenrode* [1993b] and was suggested by many other authors. A study of the influence of sector boundary crossings on the timescales and rise phases of particle events has concluded that these do not affect particle profiles [*Kahler et al.*, 1996]. An analysis by *Sanderson et al.* [2001] showed that discontinuities in the magnetic field can act as barriers for particle propagation on much smaller timescales than the one considered in this paper.

[58] At 5 AU we do not expect changes in the magnetic polarity at the spacecraft to be in time coincidence with crossing of the neutral line at the Sun. This is because the coronal magnetic fields evolve on the Sun over the timescales necessary for the magnetic polarity to be carried out to 5 AU. Consequently we do not look at correlations of particle intensity changes with changes in magnetic polarity at the spacecraft.

[59] From an analysis of the plots of the model coronal source surface field provided by the Wilcox Solar Observatory (courtesy of J. T. Hoeksema), we can see that in August 1998 Ulysses was quite likely to remain connected to a single magnetic sector for the whole duration of the SEP event. In January 1999 on the contrary, the spacecraft

must have connected to two regions of different magnetic polarity over a solar rotation.

### 3.5. Conclusions and Future Work

[60] In this paper we discussed how four models on the origin of decay-phase SEPs would interpret the observations at 5 AU in the low energy range in the long-duration particle events of 24 August 1998 and 20 January 1999.

[61] A model of continuous shock acceleration does not provide a straightforward explanation of the very different time profiles. The possibility that this mechanism is the source of the energetic particles cannot however be excluded. As far as the reservoir/bottle model is concerned, more measurements would be needed to resolve whether a barrier to particle propagation is present in the outer heliosphere, and to clarify the nature and spatial extent of the barrier.

[62] An important feature of the observations is the strong energy dependence of the shape of the profiles seen in January 1999. The ~1 MeV energy protons do show a marked depletion. This effect is present but less evident in the 5.4–25 MeV protons, and only barely visible for higher energy protons. This energy dependence of the effect is consistent both with the reservoir and the interplanetary scattering hypotheses. The anisotropy measurements presented in section 2.4 did not clearly point toward one of the four mechanisms described above.

[63] Our conclusion is that none of the four models of decay-phase SEPs can explain easily and with high degree of confidence the SEP measurements presented in this paper. The possibility however exists that the profiles observed might be a result of a combination of the mechanisms discussed in sections 3.1–3.4.

[64] Generally speaking, our analysis of the profiles of ~MeV protons at 5 AU from the Sun has shown that the depletion in particle intensities observed on 20 January 1999 is not associated with local abrupt changes in the solar wind speed or the magnetic field polarity. Our data show a remarkable degree of decoupling of the particle fluxes from the local solar wind conditions. All indications are therefore that the energetic particles we observe are not accelerated locally.

[65] The above discussion relies on the interpretation of the low-energy proton data at Ulysses in January 1999 as characterized by a depletion in flux. This assumption and the evidence supporting it were discussed in section 2.3. The possibility that the second enhancement might be due to another unrelated phenomenon however exists. The authors hope that additional data on these events or analysis of similar events will clarify this issue in future.

[66] Two physical processes which were not discussed in this paper and might play a role in shaping SEP profiles at 5 AU should also be mentioned: particle cross-field diffusion in interplanetary space and the mechanisms for energy losses between 1 and 5 AU.

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