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Ulysses observations of solar energetic particles from the July 14, 2000 event at high heliographic latitudes

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Abstract. At the time of the flare on the Bastille Day of 2000, Ulysses spacecraft was at 3.17 AU from the sun, high heliographic latitude of 62° South, and 116° in longitude east of the Earth. The event produced large fluxes of energetic particles up to energies >100 MeV at both Ulysses and the Earth. Enhancements of energetic particles were immediately observed at the Earth, their onset times consistent with the velocity dispersion due to the streaming of particles along magnetic field lines from the CME shock in the corona to the Earth. To the contrary, at Ulysses, the energetic particles from the solar event were not detected until 4-11 hours later, and the increases of particle intensity were much more gradual. The onset times of particles at Ulysses were not organized by particle speed; rather they depended on both particle rigidity and speed. Model analyses using the focused transport theory and a simple diffusion model indicate that the particles seen by Ulysses were injected around the time of peak flaring at 1024UT and that the particle transport to Ulysses requires much smaller mean free path than from the sun to the Earth. Unless the magnetic turbulence could cause such slow particle transport at high latitudes, the observations suggest that Ulysses was not directly connected by magnetic field lines to the shock driven by the CME. Energetic particles reached the latitude at Ulysses by transport across nominal Parker magnetic field lines. Such efficient latitudinal transport may be indicative of random motion of magnetic field line in the solar corona that causes braided magnetic field lines in the heliosphere.

1. Introduction

Solar energetic particles accelerated in the solar coronal by either solar flares or the shocks driven by coronal mass ejections (CMEs) can be used to test the models for heliospheric magnetic field. Because the source location of solar energetic particles can be known for many events, they are particular suitable for studying the mechanism of particle propagation in heliospheric magnetic fields. Mazur et al. (2000) recently found with measurements by the ACE spacecraft that the intensities of solar energetic particles from impulsive solar flares have short time-scale (~3 hr) dropouts occurring simultaneously across all energies. This feature is caused by the convection of magnetic field tubes passing the spacecraft that are alternately filled and devoid of particles from a small impulsive flare on the Sun (Giacalone et al. 2000). They argued that this is an evidence for the mixing of interplanetary magnetic field lines due to the random walk of field in the solar atmosphere. Solar energetic particles from large gradual events do not show the dropout because the size of the sources (i.e. CME shocks) is too large.

In this paper, we study the propagation of solar energetic particles from large gradual events with a different approach. We use simultaneous observations at Ulysses and Earth in the inner heliosphere, which are separated substantially in heliographic latitude and longitude. We report the behavior of solar energetic particles produced by the CME shock on Bastille Day of 2000. By comparison of the time profiles of energetic particle intensities observed at the two locations we discuss their implication to the mechanisms of particle propagation in the heliospheric magnetic fields.

2. Observations

We use energetic particle measurements from the High-Energy Telescope (HET) experiment on Ulysses and similar measurements at the Earth by GOES and SOHO. We have chosen GOES to represent the observations of energetic protons seen at the Earth because the counting rates from this spacecraft did not suffer saturation due to the presence of high levels of radiation from the Bastille Day event. Measurements of energetic electrons are from the COSTEP experiment on SOHO.

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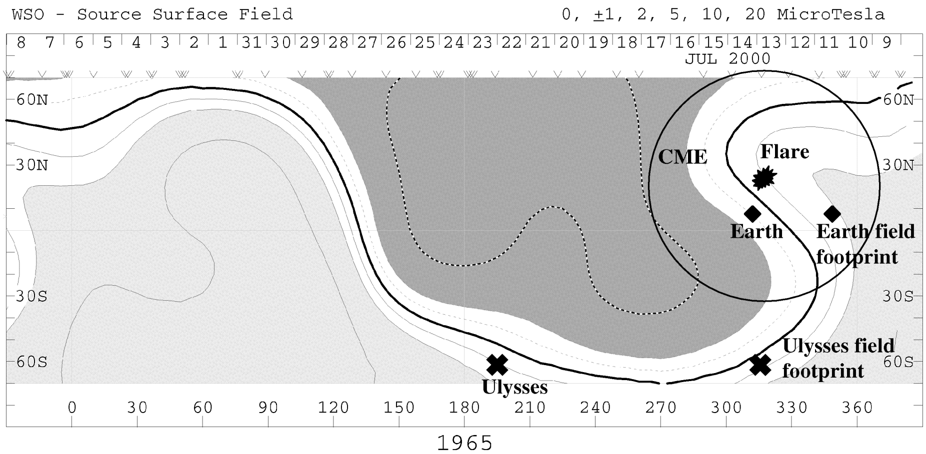

Fig. 1 – The location of the flare and the projections of spacecraft locations on the solar surface with a solar magnetic field configuration obtained by Wilcox Observatory on the background. The footpoints of magnetic field lines to Ulysses and the Earth are calculated with the Parker magnetic field model with an observed solar wind speed of 600 km/s. A rough guess for the size of the CME is shown by the circle.

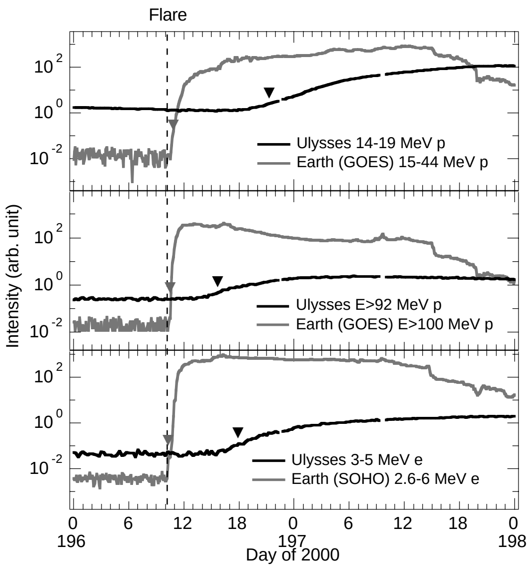

Fig. 2 – Measurements of solar energetic particle intensities by Ulysses and spacecraft at the Earth. The particle intensities are counting rates in the channels responding mainly to the particles indicated in the graph. The triangles indicate the times of onset of particles at the two locations.

The locations of the spacecraft and the solar event on July 14 (day 196) of 2000 are shown in Figure 1 as a projection on to solar source surface with solar magnetic field configuration on the background. Ulysses was located at 3.17 AU, 62°S in heliographic latitude and 116° east from the Earth in heliographic longitude. Also shown in Figure 1 are the footpoints of magnetic field lines that pass through Ulysses and the Earth obtained by calculation using the Parker magnetic field model with a measured solar wind speed of 600 km/s. The footpoint of the field line to Ulysses is actually quite close to location of the flare in longitude although they are separated by ~80° in latitude. An X5 solar flare at 22°N 07°W relative to the Earth started at 1003UT and peaked at about 1024UT. The event produced a halo CME mostly heading towards the Earth, so its latitudinal and longitude extension cannot be well measured by coronagraph. We use a circle to indicate a rough scale size of the CME at an early phase of the event. The circle is about 90° in diameter, which may be an over-optimistic number because it is much larger than a typical CME size of 47°(Hundhausen, 1993). Evidence from Nancay radio observations (Pick et al. 2001) show that the CME did not reach beyond 30° S in early phase of the event. Solar wind and magnetic field measurements on Ulysses show that the CME did not reach Ulysses. Later in time, because of huge dose of radiation from the solar energetic particles of this event, SOHO was not able to image the solar corona. Thus the evolution of the CME and its shock is not known.

Figure 2 shows a comparison of solar energetic particle measurements obtained at Earth and Ulysses on days 196-197. At the Earth, relativistic electrons started to increase minutes after the commencement of the solar flare, high-energy protons appeared later and were followed by low-energy protons. This is consistent with the velocity dispersion for the particles to stream from the sun to the Earth, and it also indicates that there is direct magnetic connection between the Earth and the CME shock. At Ulysses, energetic particles started to increase 4-11 hours after the solar flare. High-energy protons arrived first, followed by relativistic electrons and then by low-energy protons. This observation suggests that the propagation of first-arriving particles from the sun to Ulysses was not through streaming along field lines, since otherwise the electrons would have arrived first. The gradual increases of particle intensities are consistent with diffusive transport. To further test this conclusion, we have plotted in Figure 3 the particle onset times as a function of particle speed. We define the onset time to be the time at which particle intensity is 5 standard deviations above its pre-flare background averaged over 12 hours. The lines are the predictions of particle arrival time by streaming. The injection time of particles at the sun is taken to be 1009UT which is in between the commencement and peak of the X-flare. Compared with the predictions we found that the onset times are consistent with the Earth being directly connected to the source of particles on the sun. The particle onset times at Ulysses appeared much later than the prediction for streaming along field lines from the sun. In particular, the onset times of the two HET relativistic electron channels at $c/v \approx 1$ break the trend of the streaming prediction. On the other hand, since the electrons in the two HET channels (3-5 and 5-10 MeV) have much lower rigidity than the protons, a rigidity dependent transport may be a way of controlling the transport to Ulysses. This again suggests that the propagation to Ulysses should be a diffusive process. In the case of diffusion the onset times of particles depend on the diffusion coefficient, which often is a function of particle speed and rigidity.

Ulysses was able to obtain anisotropy measurements for the energetic particles. The anisotropy is along the local magnetic field coming from the general direction of the sun. The amplitude of the first-order anisotropy started with a modest value of ~0.4 and the distribution became more isotropic later in the particle event.

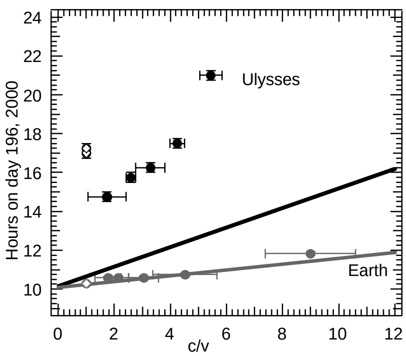

Fig. 3 – Onset times of energetic particle increases observed at Ulysses and the Earth as functions of particle velocity. The lines are derived from prediction by assuming that particles stream along magnetic field lines from the sun to the spacecraft.

3. Discussion

There are two possible mechanisms to explain the delay of energetic particle onsets at Ulysses:

(1) *Cross-field transport from low to high latitude.* It is unlikely that given a flare occurring at 22°N its CME can reach 62° S. From the LASCO coronagraph observations and Nancay radio observations (Pick et al. 2001), the CME and its associated shock seem unable to reach latitude beyond ~30° S in the early phase of the event. The solar wind and magnetic field measurements on Ulysses have put a limit on the final size of CME shock. If the shock driven by the CME later did not expand enough in latitude to reach the footpoint of the magnetic field line to Ulysses (see Figure 1) or there were no subsequent undetected large CMEs at high southern latitudes, particles accelerated by the CME shock mostly in low latitude region had to transport across magnetic field lines in order to reach the Ulysses latitude. This is because the Ulysses was only 3.17 AU from the sun, over which range the heliospheric magnetic field cannot make large enough latitude excursion (~30°) even with most aggressive parameters in the Fisk (1996) model for the heliospheric magnetic field. The large particle fluxes at Ulysses, particularly those of low-energies, suggest particle transport across latitude was remarkably easy. While it could be the case that during the solar disturbance that magnetic field turbulence near the sun could be strong enough to drive fast particle cross-field diffusion, a more reasonable possibility is that the heliospheric magnetic field lines are braided due to the random walk in the solar atmosphere (Jokipii and Parker, 1969; Giacolone et al. 2000) so that a small cross-field diffusion by magnetic turbulence can be amplified into a large latitudinal transport. Assuming that Ulysses was 30° away from the source of particle, we need a latitudinal diffusion coefficient for the random walk of magnetic field line of about 1.5×10^{-2} rad^2/day, which seems to be too large for just super granulation on the sun to work alone. Some other mechanisms, such as reconnection of magnetic field in the corona, may be required to enhance the latitudinal transport.

The delayed gradual increases of particles seen at Ulysses suggest that particle transport from the sun to Ulysses should be a diffusive process. If we assume cross-field diffusion, the latitudinal diffusion coefficient is $\kappa_{\theta\theta} = \kappa_\perp / r^2$, where $\kappa_\perp$ is a cross-field diffusion coefficient in the spatial coordinate. And if we assume that $\kappa_\perp$ is inversely proportional to the heliospheric magnetic field strength, i.e., $B \sim \sqrt{1+(\Omega r\sin\theta / V_{sw})^2} / r^2$, where Ω is the rotation rate of the sun, r the radial distance, θ solar co-latitude, and V_{sw} solar wind speed, then latitudinal diffusion is more efficient at small radii from the sun. However, a mere cross-field diffusion would result in little anisotropy in the flux, which is not consistent with Ulysses anisotropy measurements. A possible explanation for the anisotropy is that particles finished their cross-latitude transport in regions close to sun due to smaller distance between field lines and then propagate along magnetic field line to the large radial distance of Ulysses.

(2) *Small mean-free path of particle transport on high-latitude field lines.* There is still a possibility that the CME shock might have propagated to the latitude of the footpoint of the field line to Ulysses. Energetic particles seen at Ulysses can be a result of propagation along magnetic field lines from a late shock to the spacecraft. In this case, the delay of particle onsets can be naturally explained by the propagation time needed for the shock to reach high latitude.

However, in order to make this mechanism to work for the Ulysses observations, the mean free path along the magnetic field must be small, so that the particles were sufficiently scattered before they reach Ulysses because the velocity dispersion of the onset times of particle increases has clearly been broken (Figure 4) as is the case particularly for the relativistic electrons. To test this, we solved the focused transport equation numerically (Roelof, 1969, Hatzky and Kallenrode, 1999) for particle transport strictly along magnetic field lines and we compare the time profiles of high-energy protons to the model calculations in order to derive the particle mean free path. In the model calculations, we assume that the particles are injected on the solar surface with a δ-injection, which is likely to be true for high every (>100 MeV) particles because the CME shock is only strong enough to accelerate particles to this energy low in the corona. The particles propagate along the Parker spiral magnetic field with a solar wind speed of 600 km/s to the spacecraft. We assume that the pitch-angle diffusion coefficient is independent of the particle pitch angle. The particle mean free path parallel to the magnetic field, which is directly related to the pitch-angle diffusion coefficient (see Roelof, 1969), is taken to depend on the spatial location as $\lambda_{\parallel} = \lambda_0[1+(\Omega r \sin\theta / V_{sw})^2]$. Such a choice of particle mean free path coincides with a constant mean free path in the radial direction $\lambda_r = \lambda_0$. In Figure 4 we display the results of our model calculations with observations of particles obtained by GOES (A) and Ulysses (B). A constant radial mean free path of 0.083 AU can fit the ramp-up as well as the decay phase of particle intensity seen at the Earth quite well (Figure 4A). For the observations at Ulysses, however, we have to reduce the radial mean free path by 10-19% in order to fit the ramp-up part of the intensity time profile. That means particle transport to the same radial distance is slower at high latitude than at low latitude. The particle mean free path parallel to the magnetic field at high latitude has to be even smaller compared to that at low latitude at the same radial distance, because the magnetic field line at high latitudes is more radial. The difference in the parallel mean free path between high and low latitudes increases with the radial distance from the sun. The poor fit to the decay phase of particle intensity at Ulysses probably indicates that the parallel mean free path at high latitude has to be adjusted to a higher value for large radial distances. But even so, we found that the mean free path at high latitudes is significantly smaller than at low latitudes. Focused transport models with constant parallel mean free path suggest that the parallel mean free path at high latitudes must be at least 50% smaller than at low latitudes, although these models cannot produce good fits to the ramp-up and the decay phase of the intensity time profile simultaneously under any choice for the value of the mean free path.

It should be noted that in the calculations displayed in Figure 4, we assume particles are injected on the sun at the peak of the solar flare, that is, 1024UT. We also have tried a possibility that the injection of particles is significantly delayed at high-latitude field lines, corresponding to a possible propagation delay of the CME shock to high latitude or possible subsequent high-latitude CMEs which seem to exist in the Nancay radio data (Pick et al. 2001). But we found it is very difficult to fit the focused transport model even to the ramp-up part alone. For example, if we choose to fit the peak of intensity time profile to the model calculation with $\lambda_r = 0.083$ AU, we have to delay the particle injection by 2-3 hours; then we found the onset of particles at Ulysses are significantly too early compared to the model. We have also used a simple diffusion model (Reid, 1964) to fit the intensity profiles observed at both the Earth and Ulysses. The best fits to the model yield a particle injection time at 1025UT with an error smaller than 1 minute for both low and high latitudes. These model calculations suggest that particles are more likely injected around the time of the solar flare peak at 1024UT. The flare at that time is very energetic and the associated CME is fast, so its shock is more likely to be able to accelerate particles to very high energies, although we cannot completely rule out the possibility that a later solar flare or CME might be responsible to the high-energy particles seen at Ulysses. If the particles are injected at that time, these particles have to be accelerated at low latitudes because the shock has not yet propagated to high latitude. Thus the particles must undergo an efficient cross-field transport.

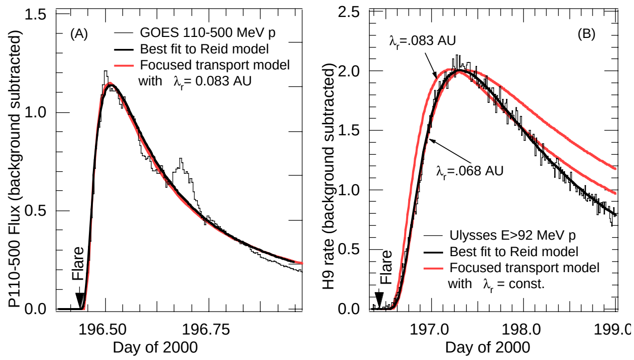

Fig. 4 – Intensities of solar energetic particle observed at the Earth (A) and Ulysses (B) with their best fits using the Reid diffusion model and calculations by the focused transport theory.

4. Conclusion

Comparisons of energetic particle observations at Ulysses and the Earth show that the modes of particle propagation to the two locations are quite different. Evidence from the particle onset times indicates that the Earth was directly connected by magnetic field lines to the CME shock as the source of the particles. However, increases of particles at Ulysses were delayed and gradual, indicating that the propagation to Ulysses might be through a diffusive transport mechanism. Our analysis suggests that the energetic particles may have reached the latitude of Ulysses mainly through a very efficient cross-field transport from the low latitude CME shock

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