

Ulysses Observations of Solar Energetic Particles From the July 14 of 2000 Event at High Heliographic Latitudes

Ming Zhang¹, R. B. McKibben, and C. Lopate
Enrico Fermi Institute, University of Chicago

¹ Now at Department of Physics and Space Science
Florida Institute of Technology

J. R. Jokipii and J. Giacalone
Department of Physics, University of Arizona

M.-B. Kallenrode
Department of Physics, University of Osnarbruck

H. K. Rassoul
Department of Physics and Space Science, Florida Institute of Technology

Abstract

At the time of the solar flare on July 14 (Bastille Day) of 2000, the Ulysses spacecraft was at 3.17 AU from the sun, 62° South in heliographic latitude, and 116° in longitude east of the Earth. Solar wind and magnetic field measurements by Ulysses indicate that the CME associated with this event had a limited size in both latitude and longitude, although it was a halo CME as seen in the SOHO coronagraph images. 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, with their onset times consistent with the velocity dispersion due to the streaming of particles along magnetic field lines from the location of particle acceleration 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 in different energy channels were not organized by particle speed; rather they depended on both particle rigidity and speed, indicating that the transport of particles to Ulysses at high latitudes had a diffusive nature. The first-order anisotropy in the 40-90 MeV proton flux was significantly larger than what is expected from the Compton-Getting effect for many hours after the onset. The direction of the first-order anisotropy was not along the projection of local magnetic fields onto the scan plane of the detector and it was not affected by the polarity of the field either, indicating that the particles did not arrive at Ulysses through propagation along magnetic field lines and instead there was a large

cross-field diffusion flow in the presence of a cross-field density gradient pointing towards the low latitude direction. All these observations are consistent with easy particle transport across magnetic field lines. The apparent difficulty for the theory is that the observations require a cross-field diffusion that is too fast to be explained by random walk of field lines due only to supergranulation.

1. Introduction

Energetic particles from ~ 1 MeV to a few GeV observed in the heliospace may come from various acceleration sources. They may be galactic cosmic rays, anomalous cosmic rays accelerated by the termination shock, energetic particles accelerated by interplanetary shock, or solar energetic particles accelerated either by coronal mass ejection (CME) shocks in the corona or by the solar flares. Since most of the energetic particles observed by spacecraft are not produced locally, the observations of these particles contain propagation effects because they must travel in the heliospheric magnetic field from their source location to a spacecraft. Thus these energetic particles can be used as remote sensors for studying the structure of heliospheric magnetic fields.

Previous studies from Ulysses measurements (see reviews by McKibben, 2001; Lanzerotti and Sanderson, 2001) found evidence that energetic particles can be transported across heliospheric latitude and longitude quite easily. During Ulysses' first encounter with solar polar regions in the 1994-1995 solar minimum, it was discovered that the energetic particles accelerated by low-latitude corotating shocks can appear above the solar poles and that the intensities of both galactic and anomalous cosmic rays over the poles are still modulated recurrently by the passage of the corotating interaction regions (CIRs) at low latitudes. If the heliospheric magnetic fields obey the Parker model, the Ulysses observations indicate that energetic particles must be able to move across magnetic field lines very easily. In fact, the required cross-field transport is too fast to be explained by the observed levels of magnetic turbulence in the solar wind. Two alternative models for the heliospheric magnetic field have been put forward. Jokipii and Parker (1969) suggested that magnetic field lines are moving constantly due to the supergranulation on the sun. As a result, when the magnetic field is carried out radially by the solar wind the trajectory of magnetic field lines in the interplanetary space exhibits random walk in both latitude and longitude (braided field lines). Locations in the heliosphere at different latitudes may be connected by a field line by chance. Particles following a magnetic field line can then move to different latitudes quite easily. Evidence for such a process was found by Mazur et al. (2000). Fisk (1996), on the other hand, suggested that heliospheric magnetic field lines might be undergoing systematic motion in latitude due to the

differential rotation of the sun. Over a period of about a few months, the latitude excursion of field lines can be several tens of degrees. This means that a location at high latitude (e.g. Ulysses) may be connected by a magnetic field line to a low latitude region of the heliosphere at large radial distance (~ 15 AU). In this model, Ulysses saw recurrent CIR-accelerated particle and cosmic ray modulation because it was periodically connected by magnetic field lines to a distant CIR.

Solar energetic particles can be used to test the models for heliospheric magnetic fields. According to the current paradigm (Reames, 1999), small impulsive solar energetic particle events are related to solar flares, while solar energetic particles in large gradual events are produced by shocks driven by large CMEs. Because the source location of solar energetic particles can be known for many events, they are 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 (Giacolone et al. 2000). They argued that this is an evidence for the mixing of interplanetary magnetic field lines due to 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 report the behavior of solar energetic particles produced in the particle event on July 14 (Bastille Day) of 2000. We study the propagation of solar energetic particles from the large gradual event by using simultaneous observations at Ulysses and the Earth, which were separated substantially in heliographic latitude and longitude at that time. By comparison of the time profiles of energetic particle intensities observed at the two locations we discuss its implication to the mechanisms of particle transport in the heliospheric magnetic fields.

2. Observations

We use energetic particle measurements from the High-Energy Telescope (HET) of the COSPIN consortium on Ulysses. Observations at the Earth are taken from GOES, SOHO and

IMP-8. We choose GOES measurements to represent the observations of energetic protons seen at the Earth because the flux measurements from this spacecraft did not suffer counting rate saturation due to the presence of high radiation level from the Bastille Day event. Measurements of energetic electrons from GOES are not usable, so we choose to use the electron data from the COSTEP experiment on SOHO. Energetic particle data from GOES and SOHO are provided in counting rates. Because the response (geometric factor) of the instruments on GOES and SOHO is not known to us, we choose to use the data from the University of Chicago charged particle experiment on IMP-8 where absolute flux measurements are required for comparison with Ulysses measurements. For details of the instruments, readers may see Simpson et al. (1992) for the HET on Ulysses, the Web site <http://www.sao.noaa.gov/goes/goes.html> for the GOES measurements, Müller-Mellin (1995) for the COSTEP on SOHO, and Garcia-Munoz et al. (1987) for the IMP-8 instrument.

We also use solar wind and magnetic field measurements at Ulysses and the Earth (ACE and IMP-8). These data were obtained from the National Space Science Data Center (NSSDC).

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 the solar wind source surface at 3 solar radii with a solar magnetic field configuration (obtained from Wilcox Observatory) 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 on the solar wind source surface of magnetic field lines that pass through Ulysses and the Earth. The footpoints are calculated using the Parker magnetic field model with a measured solar wind speed of 600 km/s at the time of the event by Ulysses and IMP-8 spacecraft at Earth. We assume that the speed of the solar wind from a fixed solar longitude does not vary drastically over a time period of ~8 day during which the solar wind propagates to Ulysses at ~3 AU. The footpoints do not vary much even if the solar wind speed has an uncertainty of ± 100 km/s. The footpoint of the field line to Ulysses is actually quite close to the longitudinal location of the flare 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 circle in Figure 1 represents an approximate size of the CME at the time around 1054UT (Plate 1, we assume that the shell on the west side of the sun is a part of the CME heading side way). The CME is a halo CME with its center heading approximately

towards the Earth, so its latitudinal and longitude extension cannot be well determined with the LASCO C2 coronagraph from SOHO because of the line-of-sight effect. We use a circle to indicate a rough scale size of the CME at an early phase of the event (up to ~1 hour after the onset of the solar flare). The circle is centered at the flare and about 90° in diameter, which may be an over-optimistic number because it is much larger than a typical CME size of 47° (Huundhausen, 1993). Evidence from Nancay radio observations (Pick et al. 2001) shows that the CME did not reach beyond 30° S in the early phase of the event. Later in time, because of interference from the high intensities of solar energetic particles produced by this event, SOHO was not able to image the solar corona. Thus the later evolution of the CME and its shock is not known.

Figure 2 shows an overview of energetic particle, solar wind and magnetic field measurements obtained at the Earth and Ulysses covering day 195 to day 209 of 2000. Energetic particles at the Earth, both protons and electrons, started to increase almost immediately after the solar event at 1024UT on day 196, but energetic particles did not show up at Ulysses until several hours later and the increases were gradual. The peaks of the particle intensities at Ulysses were much smaller and later than those at the Earth. As shown by the solar wind and magnetic field measurements, a shock driven by the CME arrived at the Earth on day 197, with a speed greater than 1000 km/s, but in the next 14 days following the event there are no signatures of an associated shock, CME or magnetic cloud at Ulysses. (Some enhancements in magnetic field observed at Ulysses on days 203-209 are due to the fact that Ulysses returned to slow solar wind streams after a rarefaction region). These observations indicate that the CME was not large enough in longitude and latitude to reach the location of Ulysses (see Figure 1). Thus this CME was certainly not global in terms of its size, although it was quite energetic.

The behaviors of energetic particle onsets at the Earth and Ulysses are quite different. Figure 3 shows the measurements for days 196-197. At the Earth, relativistic electrons started to increase a few minutes after the commencement of the solar flare. High-energy protons appeared later, followed by low-energy protons. This is consistent with the velocity dispersion expected for the particles to stream from the sun to the Earth. It also indicates that there was a 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, because otherwise the relativistic electrons would have arrived first. The increases of particle intensities at Ulysses were gradual, which is consistent with a diffusive transport. To further test this conclusion, we have plotted in Figure 4 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 times the standard deviation above its pre-flare background averaged over 12 hours. We have chosen a long enough averaging time interval for the pre-flare background so that its statistical uncertainty is negligible. Then the standard deviation of particle intensity is mainly due to the statistical uncertainty of the counting rate during the accumulation time interval around the onset. The lines are the predictions of particle arrival time assuming they stream along magnetic field lines to the spacecraft. 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, the observed 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 from 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 Ulysses HET channels (3-5 and 5-10 MeV) have much lower rigidity than the protons, a rigidity dependent transport can be a solution to explain the onset of particle increase at Ulysses. This again suggests that the particle propagation to Ulysses be a diffusive process. In the case of diffusion the onset times of particles should depend on the diffusion coefficient, which often is a function of particle speed and rigidity.

The HET on Ulysses is mounted with its aperture perpendicular to the spin axis of the spacecraft (Figure 5), so we are able to obtain some anisotropy measurements for energetic protons in the energy range of 40-92 MeV (H45 sector rate). We have fitted 8-sector H45 hourly average counting rates with a sum of harmonics up to the second order (see the figure caption). Figure 6 shows the obtained fitting parameters. Substantial first order anisotropy appears as soon as the counting rate exceeds the statistical threshold for meaningful determination of anisotropy, and its magnitude diminishes very gradually. Possible sources of the first order anisotropy can be (a) the Compton-Getting effect, (b) streaming of particles along the magnetic field lines or (c) a particle density gradient across the magnetic fields. At the energy of the H45 sector channel, the expected maximum anisotropy from the Compton-Getting effect is about 4% for the observed

power law spectrum with a slope of about -2 for this event if the solar wind speed is 650 km/s and lies in the scan plane of the detect. In fact, because the solar wind is almost perpendicular to the scan plane (see Figure 5), we expect a much smaller Compton-Getting effect. The magnitude of the first order anisotropy shown in Figure 6 is over 10% for most of the time period and in the early phase it is over 50%. This indicates that the first order anisotropy appearing in this event cannot come from the Compton-Getting effect. The direction of the first order anisotropy (Φ_1) is not along the magnetic field direction projected onto the spin plane for most of the time during the phase of increasing flux. In particular, for the time period 12:00 – 24:00 UT on day 197, the first order anisotropy is approximately perpendicular to the projected magnetic field direction. This behavior indicates that the first order anisotropy cannot come from particle streaming along the magnetic field lines. In fact, because the magnetic field is almost perpendicular to the scan plane of the detector (see the Δ Mag panel), we expect a smaller anisotropy even if there is significant streaming along the magnetic fields. A particle density gradient across the magnetic field can produce an off-field first order anisotropy either through gyromotion effect in which $A_1 = r_g \hat{\mathbf{b}} \times \nabla n / n$ (r_g particle gyroradius; $\hat{\mathbf{b}}$ unit vector of magnetic field direction; n particle density) or through cross-field diffusion in which $A_1 = -\kappa_{\perp} \nabla n / (vn)$ (κ_{\perp} diffusion coefficient; v particle speed). We notice that the direction of the first-order anisotropy does not change when the magnetic field switches its polarity around 00:00UT on day 197. This rules out the contribution from the $A_1 = r_g \hat{\mathbf{b}} \times \nabla n / n$ anisotropy unless the gradient of particle density switches to the opposite direction at the same time. The $A_1 = r_g \hat{\mathbf{b}} \times \nabla n / n$ anisotropy is expected to be small because the particle gyroradius is much smaller than the gradient scale of the particle density on the heliospheric size. Therefore, we conclude that there must be a large cross-field diffusion flow that can produce the observed off-field first order anisotropy. The direction of the diffusion flow is consistent with a particle density gradient approximately pointing towards the low latitude, which is expected from the location of the CME or solar flare of the Bastille Day event. We further notice that at the beginning of the event when the projection of the magnetic field is not too much off from the direction of particle density gradient, the first-order anisotropy tends to follow the slowly changing magnetic field; however, once the magnetic field deviates too much (around 10:00UT, day 197), the anisotropy shifts its direction with respect to the magnetic field and reverts back more or less to the direction of particle density gradient. A

similar phenomenon was observed by Dwyer et al. (1997), who derived very large $\kappa_{\perp} / \kappa_{\parallel}$ ratios from the anisotropy using observations of CIR accelerated energetic particles. The off-field first order anisotropy disappears shortly after the particle flux reaches its maximum level around 04:00UT day 198. The disappearance of cross-field diffusion flow indicates that the particle density may have become nearly uniform by that time.

The second order anisotropy is less prominent than the first order anisotropy in the early phase of the particle events but it persists for many days into the particle event. The second order anisotropy direction is generally along the projected magnetic field direction for most of the time, but some significant deviation from it is also observed for some time periods. A field-aligned second order anisotropy means a dumb bell distribution that could be a result of particle injection into the magnetic flux tube plus mirroring by magnetic irregularities on the other side of the observer. It should be mentioned that the fits to second order anisotropy do not affect the result of the first order anisotropy.

3. Discussion

As presented earlier, although the flare and the CME of the Bastille Day event occurred in low latitude regions of the sun, substantial fluxes of energetic particles up to $E > 100$ MeV were detected by Ulysses at high latitudes. This is an important result for the investigation of particle propagation in the heliosphere. The question is how do the energetic particles get to the high latitudes. In the following we discuss a few possibilities: (1) direct magnetic connection between Ulysses and low latitude regions of the sun which is based on the Fisk heliospheric magnetic field model, (2) expansion of the CME shock to high latitudes and (3) cross-field particle transport based on Jokipii's suggestion of random walk of field lines. Any of these theories needs to be able to explain the major features of the observation, namely, the delayed gradual increases of particle intensity and anisotropy observed at Ulysses.

(1) Because both the solar flare and the CME of this event were observed in low latitude regions of the sun, it is most likely that the energetic particles should be produced in this region. If there is a direct connection from the particle source to high latitudes by the heliospheric magnetic field, charged particles can propagate along field lines to Ulysses at high latitude. This may be used to explain why we have observed a substantial energetic particle flux at Ulysses.

The theory is based on the Fisk heliospheric magnetic field model (1996). For this theory to work, the latitudinal excursion of heliospheric magnetic field lines must exceed roughly a few tens degrees within 3 AU (or ~ 8 days), which is too large compared to the original Fisk model. But the sun was at solar maximum in 2000 as opposed to the condition of solar minimum in the original Fisk model; it is possible that one can extend the Fisk model to the solar maximum condition to get a larger latitudinal excursion of magnetic field lines, perhaps, as Fisk has suggested recently (Fisk, 1999), by reconnection between open and close field lines near the top of active region loops and arcades, leading to “hop-scotching” of field lines across the face of the sun. However, many details of this suggestion have yet to be worked out. Some difficulties may come from magnetic field measurements, because, with such a large systematic latitudinal excursion of magnetic field lines, there should be a latitudinal component in the heliospheric magnetic field that might be observable by the magnetometer experiment on Ulysses.

Assuming that the heliospheric magnetic field lines can make very fast large latitude excursions and energetic particles can propagate to the spacecraft at high latitude through this propagation mode, one would expect to see particles streaming (first order anisotropy) out from the sun along the magnetic field and onset times of particle flux increases consistent with the prediction from direct arrival of particles by streaming along the field lines. These, however, are not what were observed. Instead, particle increases were delayed for several hours depending on their rigidity. The velocity dispersion of the onset times of particle increases has clearly been broken (Figure 4) particularly in the case of the relativistic electrons. This suggests that the mean free path of particles along the magnetic field must be small, so that the particles are sufficiently scattered before they reach the spacecraft.

To test this hypothesis, we solve the focused transport equation numerically (Roelof, 1969, Hatzky and Kallenrode, 1999) and we compare the observed time profile of proton fluxes to the model calculation in order to derive the particle mean free path. In the model calculations, we assume that the particles are initially injected on the solar surface at the time of peak flaring as a delta function, which is most likely to be true for high-energy ($E > 100$ MeV) particles because the CME shock and the magnetic field are most likely to be strong enough to accelerate particles above this energy only in the low corona. The particles then propagate along the spiral magnetic field lines to the spacecraft. Because the Fisk heliospheric magnetic model only makes slight changes to the strength of the magnetic field and to the length of the field line, we still use

the Parker magnetic model with a solar wind speed of 600 km/s as an approximation in the calculation. We assume that the pitch-angle diffusion coefficient is independent of 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 be dependent on the spatial location as $\lambda_{\parallel} = \lambda_0[1 + (\Omega r \sin\theta / V_{sw})^2]$, where r is the radial distance, θ colatitude, Ω the angular speed of solar rotation, and V_{sw} the solar wind speed. Such a choice of particle mean free path coincides with a constant mean free path in the radial direction, i.e., $\lambda_r = \lambda_0$. In Figure 7 we display the result of our model calculations in comparison with the observations 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 7A). For the observation at Ulysses, however, we have to reduce the radial mean free path by 10-20% in order to fit the ramp-up part of the intensity time profile. This means that particle transport to the same radial distance is slower at high latitude than at low latitude. The parallel particle mean free path at high latitudes has to be even smaller compared to the one at low latitudes at the same radial distance, because the magnetic field line at high latitudes is more radial. The difference of 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 find that the mean free path at high latitudes is significantly smaller than at low latitudes. If we choose a mean free path that is inversely proportional to the strength of magnetic field, we get even a smaller mean free path at high latitudes. Models calculations with constant parallel mean free path derive a parallel mean free path at high latitudes at least 50% (much) smaller than at low latitudes, and besides, 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. A small mean free path indicates that the heliospheric magnetic field has large fluctuations at high latitudes, which can be possible depending upon the condition of the solar corona. Analysis of magnetic field measurements by Ulysses and by a spacecraft in the Earth orbit might be helpful for further study.

(2) If the heliospheric magnetic field cannot make fast large enough latitudinal excursion or there is no direct magnetic connection to low latitude regions of the sun, one possibility is that the energetic particles can be directly injected onto Parker spiral field lines from acceleration

regions at high solar latitudes. This requires that the CME shock propagate to the latitude of the footpoint of the field line to Ulysses in a short time. The coronagraph measurement by SOHO cannot rule out such a possibility. Numerical simulations by Riley et al. (1997) have shown that such a latitudinal propagation of CME shocks is possible although the simulations did not tell how fast the CME shock can reach high latitudes. Because the shock comes into the field line connecting to Ulysses late, the delay of particle onsets can naturally be explained by the propagation time needed for the shock to reach high latitude.

It is unlikely, given a flare occurring at 22°N, that its CME can reach 62° S. From the LASCO coronagraph observation (Plate 1) and Nancay radio observations (Pick et al. 2001), the CME and its associated shock seem unable to reach a latitude beyond ~30° south in the early phase of the event. The solar wind and magnetic field measurements on Ulysses have also put a limit on the final size of CME shock. Let's assume that the ~4-hour delay of particle onset is entirely due to the time needed for the shock to propagate from the edge of CME (roughly 30°S) to Ulysses at 62° S. During that time the CME moves to 37 solar radii at a radial speed of ~1800 km/s. Then the average speed of latitudinal propagation is about 470 km/s. This is a large speed and its effect should be observable by speed wind measurements in other similar events, but this has never been reported. The acceleration of solar wind plasma in the latitudinal direction to this high speed is difficult to explain by the MHD theory because in the absence of volume expansion in the latitudinal direction the pressure gradient of plasma may not be large enough. Detailed modeling of shock propagation near the sun is needed for further study.

For the sake of argument, suppose that the shock can propagate to high latitudes in this short time. We can use the focused transport theory to model the particle propagation as we presented earlier in Figure 7. This analysis can be done by shifting the particle injection to a time later than the peak flaring at 1024UT. We find that it is difficult to fit the observed time-intensity profile in Figure 7B simply because if we try to fit the onset part we cannot get the right peak time of the intensity profile. 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. Using different spatial dependence of the mean free path gives the same conclusion. We can choose a model with some continuous particle injection functions to take into account the outward propagation of the shock. The effect of this is essentially the same as delay of

particle injection. In order to fit the Ulysses observation we have to input smaller particle injection when the shock is near the sun, which seems to be unrealistic because the shock and magnetic field is stronger near the sun where it can accelerate more particles to $E > 100$ MeV. Since the onset time of particles is much shorter at the Earth than at Ulysses, the delay of particle injection results in more increase of particle mean free path at low latitude than at high latitude, which is the same conclusion as the simpler model with delta particle injection. Various model calculations suggest that particles are most likely to be injected at 1024UT, the time of the peak solar flare. 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.

In addition, it is possible that there are subsequent high-latitude CMEs during the Bastille Day event. There is some evidence for high latitude CMEs in the Nancay radio data (Pick et al. 2001). But with similar analysis we found it is difficult to fit the focused transport model to the ramp-up part of the particle intensity profile.

(3) Since both the above explanations require particle propagation along the magnetic field lines, one would see the first order anisotropy of particle flux be parallel to the fields. This is not what we observed, which appears to rule out the mechanism of particle propagation along field lines. Our observation of non-field aligned anisotropy indicates that there is a large cross-field diffusion flow during the phase of increasing particle flux. The large particle fluxes at Ulysses, particularly of low-energy particles, suggest that particle transport across latitude must be remarkably easy. While it can be the case that magnetic field turbulence near the sun could be strong enough during a large solar event to drive fast particle cross-field diffusion, a more widely accepted possibility is that the heliospheric magnetic field lines are braided due to the random walk of field lines in the solar atmosphere (Jokipii and Parker, 1969; Giacalone et al. 2000) so that a small cross-field diffusion by magnetic turbulence may 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 the supergranulation on the solar surface. Some other mechanisms may be required to enhance the latitudinal transport. For example, Fisk et al (1999) suggested that magnetic field lines are undergoing continuous reconnection in the solar corona. Because magnetic field lines originating from different latitudes can connect and reconnect constantly, small-scale supergranular motion can result in much faster

latitudinal excursion of magnetic field lines at the top of solar corona. In the mean time, such reconnection process in the corona may also increase the random walk of field lines in the Jokipii model.

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 it is the cross-field diffusion, the latitudinal diffusion coefficient is $\kappa_{\theta\theta} = \kappa_{\perp} / r^2$, where κ_{\perp} is cross-field diffusion coefficient in the spatial coordinate. If we assume that κ_{\perp} is inversely proportional to the heliospheric magnetic field strength, i.e., $\kappa_{\perp} \propto B^{-1} \sim (\sqrt{1 + (\Omega r \sin \theta / V_{sw})^2} / r^2)^{-1}$, then the latitudinal diffusion is more efficient at small radii from the sun (Figure 8). The observation of a significant first order anisotropy perpendicular to the magnetic field is consistent with the cross-field diffusion. There still exists a field-aligned anisotropy because particle can stream (with defocusing effect) to the spacecraft after diffusing onto the field lines at small radial distances.

Another support for the efficient cross-field transport is evident in this energetic particle event. During the entire decay phase that lasts more than 20 days after day 200, the absolute particle fluxes at Ulysses are roughly the same as (within factor of 2) those observed at the Earth despite of their large separation in location and huge difference in flux at the initial phase of the event (see Figure 9). Reames et al. (1996; 1997) and McKibben et al. (2001) found that this is essentially true for many large solar events no matter where the spacecraft are located in the inner heliosphere. This phenomenon has also been observed for very low-energy particles (Roelof, 1991). These observations mean that gradients in the fluxes of solar energetic particles in the inner heliosphere cannot be sustained for more than a few days after an event on the sun. Diffusion is perhaps the most obvious and simplest way of relaxing gradients to achieve uniformity.

We have also used a semi-phenomenological diffusion model by Reid (1963), modified to accommodate propagation in various dimensions (see Appendix), to fit the intensity profiles observed at both the Earth and Ulysses. In the case of a very small parallel particle mean free path or strong scattering as we concluded from the previous analysis using the focused transport theory, the Reid model can be a good approximation in describing the transport of solar energetic particles. With the Reid model, we find that a 1-dimensional model fits the observations at the Earth the best while a 3-dimensional model fits the Ulysses observation the best (The dark

smooth curves in Figure 7). 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. If the particles are injected at that time, they have to be accelerated at low latitude because the shock has not have the time to propagate to high latitudes. Thus the particles arrive at Ulysses through cross-field transport.

Diffusion coefficients can be derived from the fits to the Reid model calculation with an assumption for the path of particle diffusion. Because the Reid model does not include the defocusing effect, the diffusion coefficients derived from the Reid model is larger than derived those from the focused transport equation. If we assume that particle transport is through 1-dimensional diffusion along the Parker magnetic field lines, the fits yield average parallel diffusion coefficients of $1.7 \times 10^{22} \text{ cm}^2/\text{s}$ (equivalent to a mean free path of 0.26 AU for the 100 MeV protons) for the propagation to the Earth and $1.2 \times 10^{22} \text{ cm}^2/\text{s}$ (0.19 AU mean free path) for the propagation to Ulysses. While smaller mean free path on high latitude field lines than on low latitude field lines is possible under some solar conditions, this is unexpected because Ulysses at that time was much farther away from the sun, where the magnetic field is much weaker, unless the magnetic field turbulence there is much higher than it is expected. This seems to rule out parallel propagation along the magnetic field to Ulysses. If we use the 3-dimensional model for the Ulysses observation and assume that the latitudinal distance to source particle is 30° and longitudinal separation is 0 and that the average parallel diffusion coefficient is $1.7 \times 10^{22} \text{ cm}^2/\text{s}$, same as for the Earth, the best fit yields a latitudinal diffusion coefficient of $6.9 \times 10^{-2} \text{ rad}^2/\text{day}$, which is equivalent to a perpendicular diffusion coefficient of $1.8 \times 10^{20} \text{ cm}^2/\text{s}$ (or a mean free path of 0.0028 AU) at 1 AU. If the assumed parallel diffusion coefficient is larger, we can require a smaller cross-field diffusion. The lowest limit for the perpendicular diffusion coefficient is $4.6 \times 10^{-2} \text{ rad}^2/\text{day}$, or $1.2 \times 10^{20} \text{ cm}^2/\text{s}$ at 1 AU.

4. Conclusion

We have presented observations of solar energetic particles of the Bastille Day 2000 event obtained by Ulysses at high heliographic latitude and by spacecraft at the Earth in the solar equatorial region. Comparisons of the observations at the two locations show that the modes of particle propagation to the Earth and Ulysses are quite different. Evidence from the particle onset

times indicates that the Earth was directly connected by magnetic field lines to the CME shock that is the source of the particles. The initial onsets of particles arriving at Ulysses are delayed by many hours and the increase of flux is gradual, suggesting that the propagation to Ulysses might be through a diffusive transport mechanism. The first order anisotropy of particle flux at Ulysses does not align with the magnetic fields, indicating that there is a cross-field diffusion flow in presence of particle density gradient pointing towards the low latitude. The observations suggest that energetic particles can move across magnetic field easily, a conclusion consistent with previous Ulysses observations of cosmic rays and CIR accelerated particles during the 1994-1995 solar minimum. Because the required cross-field transport is large, a random walk of magnetic field line in corona may be required, particularly for those particles with low energies. But it is not clear whether random walk of field lines caused by supergranulation on the solar surface is enough to explain the diffusion coefficient the observations require.

Acknowledgments: This work was supported in part by NASA/JPL Contract JPL-955432 and NASA Grants NAG 5-8032, NAG5-11036 and NAG5-10888. MZ thanks William Dietrich for introducing him to the Reid model used in the paper.

6. Appendix: Modification of the Reid model for study of solar energetic particle propagation in multi-dimensions.

In the original Reid model (1963), the particle transport was treated as homogeneous 2-dimensional diffusion with a phenomenological constant decay. Particles are injected as a point source at one time. This may be suitable to particle transport across magnetic field from a small source to a location close to the sun but separated in latitude or longitude. We have modified the model to other dimensions:

$$\frac{\partial f}{\partial t} = \sum_{i=1}^d \kappa_i \frac{\partial^2 f}{\partial x_i^2} - \frac{f}{\tau} \quad \text{with } f(t_0) = \delta^d(\mathbf{x}) \quad (1)$$

where the diffusion coefficient is still homogeneous but anisotropic. The solution to (1) is:

$$f(t, \mathbf{x}) = H(t - t_0) e^{-t/\tau} \prod_{i=1}^d \frac{1}{\sqrt{4\pi\kappa_i(t-t_0)}} e^{-\frac{(x_i - x_{i0})^2}{4\kappa_i(t-t_0)}} \quad (2)$$

where $H(t-t_0)$ is the Heaviside step function. We fit this function to the measurement of the particle time intensity profile to get an estimate of particle injection time and the diffusion coefficient. Since the spatial geometry is fixed, the fit can only yield a value for the sum $\sum_{i=1}^d (x_i - x_{i0})^2 / 4\kappa_i$ for multi-dimensional diffusion. Additional assumptions about the propagation mode must be made in order to derive the diffusion coefficient.

7. References

- Dwyer, J.D., Mason, G.M., Mazur, J.E., Jokipii, J.R., von Rosenvinge, T.T., and Lepping, R.P., “Perpendicular transport of low energy CIR associated nuclei”, 1997, *Astrophys. J.*, 490, L115.
- Fisk, L. A., “Motion of the footpoints of heliospheric magnetic field lines at the Sun: Implications for recurrent energetic particle events at high heliographic latitudes”, 1996, *J. Geophys. Res.*, 101, 15,547
- Fisk, L. A., Schwadron, N. A., and Zurbuchen, T. H., “Acceleration of fast solar wind by the emergence of new magnetic flux”, 1999, *J. Geophys. Res.*, 104, 19,765
- Garcia-Munoz, M., 1987, “Cosmic-ray propagation in the Galaxy and in the heliosphere - The path-length distribution at low energy”, *Astrophys. J. Suppl.*, 64, 269
- Giacalone, J., Jokipii, J.R., Mazur, J.E., “Small-Scale Gradients and Large-Scale Diffusion of Charged Particles in the Heliospheric Magnetic Field”, 2000, *Astrophys. J.* 532, L75
- Hatzky and Kallenrode, “Numerics of Interplanetary Transport”, 1999, *Proc. 25th ICRC*, 6, 320
- Hundhausen, A. J., “Sizes and Locations of Coronal Mass Ejections: SMM Observations From 1980 and 1984-1989” 1993, *J. Geophys. Res.*, 98, 13,177
- Jokipii, J.R., and Parker, E.N., “Random walk of magnetic lines of force in astrophysics”, 1969, *Phys. Rev. Lett.*, 21, 44
- Kallenrode, M.-B., and Wibberenz, G., “Propagation of particles injected from interplanetary shocks: A black box model and its consequence for acceleration theory and data interpretation”, 1997, *J. Geophys. Res.*, 102, 22,311
- Lanzerotti, L.J., and Sanderson T.R. “Energetic Particles in the Heliosphere”, 2001, , in *The Heliosphere Near Solar Minimum: Ulysses Perspectives*, Ed. A. Balogh, R.G. Marsden and E.J. Smith, Springer, Praxis, 259
- Mazur, J.E., Mason, G.M., Stone, E.C., “Interplanetary Magnetic Field Line Mixing Deduced From Impulsive Solar Flare Particles”, 2000, *Astrophys. J.*, 532, L79

- McKibben, R.B., Lopate, C., Zhang, M., “Simultaneous Observations of Solar Energetic Particle Events by IMP-8 and the Ulysses COSPIN High Energy Telescope at High Solar Latitudes”, 2001, *Space Sci. Rev.*, 97, 257.
- McKibben, R.B., “Cosmic Rays at All Latitudes in the inner Heliosphere”, 2001, in *The Heliosphere Near Solar Minimum: Ulysses Perspectives*, Ed. A. Balogh, R.G. Marsden and E.J. Smith, Springer, Praxis, 327
- Müller-Mellin, R., Kunow, H., et al., “COSTEP – Comprehensive Suprathermal and Energetic Particles Analyser”, 1995, *Solar Phy.* 162, 483
- Pick, M., and Maia, D., et al., “14 July 2000, a global coronal event”, 2001, *Solar Phy.*, submitted.
- Reames, D. V., “Particle acceleration at the sun and in the heliosphere”, 1999, *Space Sci. Rev.*, 90, 413
- Reames, D. V., Barbier, L. M., and Ng, C. K., “The Spatial Distribution of Particles Accelerated by Coronal Mass Ejection--driven Shocks”, 1996, *Astrophys. J.*, 466, 473.
- Reames, D. V., Kahler, S. W., and Ng, C. K., “Spatial and Temporal Invariance in the Spectra of Energetic Particles in Gradual Solar Events”, 1997, *Astrophys. J.*, 491, 414.
- Riley, P., Gosling, J.T., and Pizzo, V.J., “A two-dimensional simulation of radial and latitudinal evolution of a solar wind disturbance driven by a fast, high-pressure coronal mass ejection”, 1997, *J. Geophys. Res.*, 102, 14,677.
- Roelof, E.C., Gold, R., Simnett, G.M., et al., “Low-energy solar electrons and ions observed at Ulysses February-April 1991: The inner heliosphere as particle reservoir”, 1992, *Geophys. Res Lett.*, 19, 1243
- Roelof, E.C., “Propagation of solar cosmic rays in the interplanetary magnetic field” 1969, in *Lectures in High Energy Astrophysics*, Ed. H. Ogelmann and J. R. Wayland, NASA SP-199, 111
- Simpson, J.A., Anglin, J.D., Balogh A., et al. “The Ulysses Cosmic Ray and Solar Particle Investigation”, 1992, *Astron. & Astrophy. Suppl.*, 92, 365

Figure captions

Plate 1 – LASCO C2 coronagraph image from SOHO.

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, solar wind speed and magnetic field strength obtained by Ulysses and spacecraft at the Earth. The particle intensities are shown in counting rates of the channels responding mainly to the particles indicated in the graph. The magnetic field at the earth has been scaled down by factor of 20 for comparison purpose.

Fig. 3 – Same as Figure 2 with zoomed scale. The triangles indicate the times of onset of particles at Ulysses and the Earth.

Fig. 4 – Onset times of energetic particle increases observed at Ulysses (dark) and the Earth (gray) as functions of particle velocity. The open symbols are for relativistic electrons and filled ones are for protons. The lines are derived from prediction by assuming that particles stream along magnetic field lines from the sun to the spacecraft.

Fig. 5 – The geometry of Ulysses HET sector measurements during the Bastille Day event. The XYZ are despun spacecraft coordinates, with the Z-axis pointing towards the Earth and the X-axis in sun pulse direction. Reference to the normal RTN heliospheric coordinates is also shown.

Fig. 6 – Fitting parameters to the Ulysses HET sector H45 hourly average counting rates for 40-92 MeV protons. The fitting function is a sum of harmonics up to the second order, i.e., $C_0[1 + A_1 \cos(\varphi - \Phi_1) + A_2 \cos(2\varphi - 2\Phi_2)]$, where C_0 is the spin average counting rate (bottom panel), A_1 and A_2 are the amplitude of first and second order anisotropies and Φ_1 and Φ_2 are the direction of the anisotropies to the X axis of spacecraft despun coordinate system. The projection of the (5-min average) magnetic field direction (either the + signs for \mathbf{B} or the - signs for $-\mathbf{B}$) on to the plane perpendicular to the spin axis of the spacecraft is shown in comparison with the anisotropy direction. The Δ Mag is the elevation angle of magnetic fields to the scan plane of Ulysses HET. The lines in the Φ_1 and Φ_2 panels indicate the direction pointing towards the low latitude (i.e. along the N axis in the RTN coordinate system).

Fig. 7 – 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. Fits to the Reid model yield the time for particle injection and diffusion coefficient (see text).

Fig. 8 – Scaled latitudinal diffusion coefficients as functions of radial distance from the sun. It is assumed that perpendicular diffusion coefficient is inversely proportional to the heliospheric magnetic field strength.

Fig. 9 – Absolute fluxes of energetic particles observed at Ulysses and the Earth. It is an example showing that the particle fluxes at two locations often become roughly equal a few days into the event.

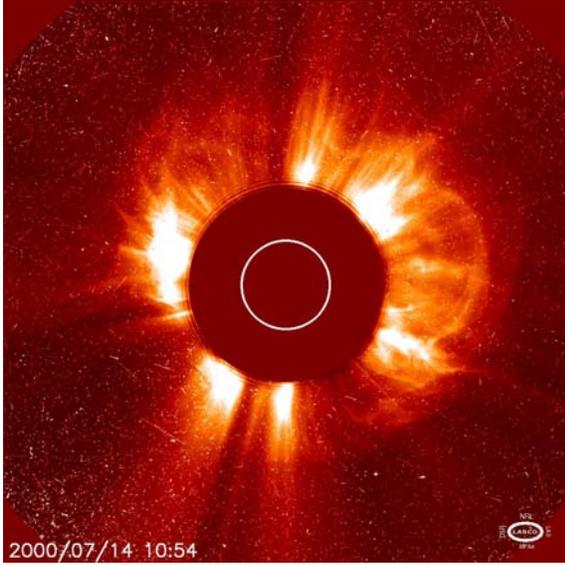


Plate 1

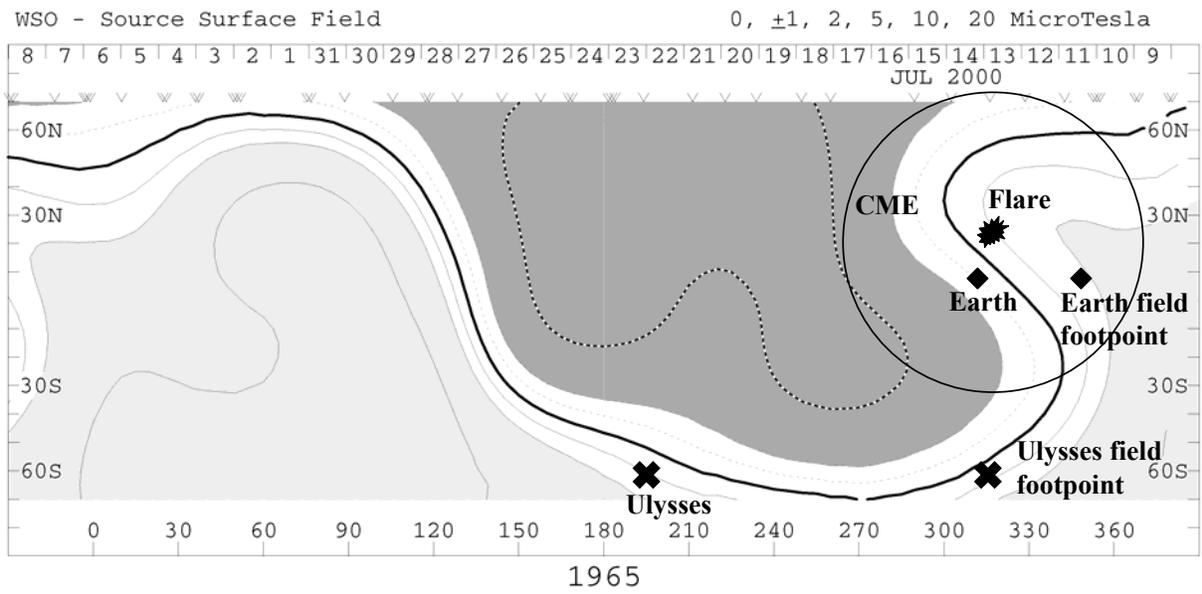


Fig. 1

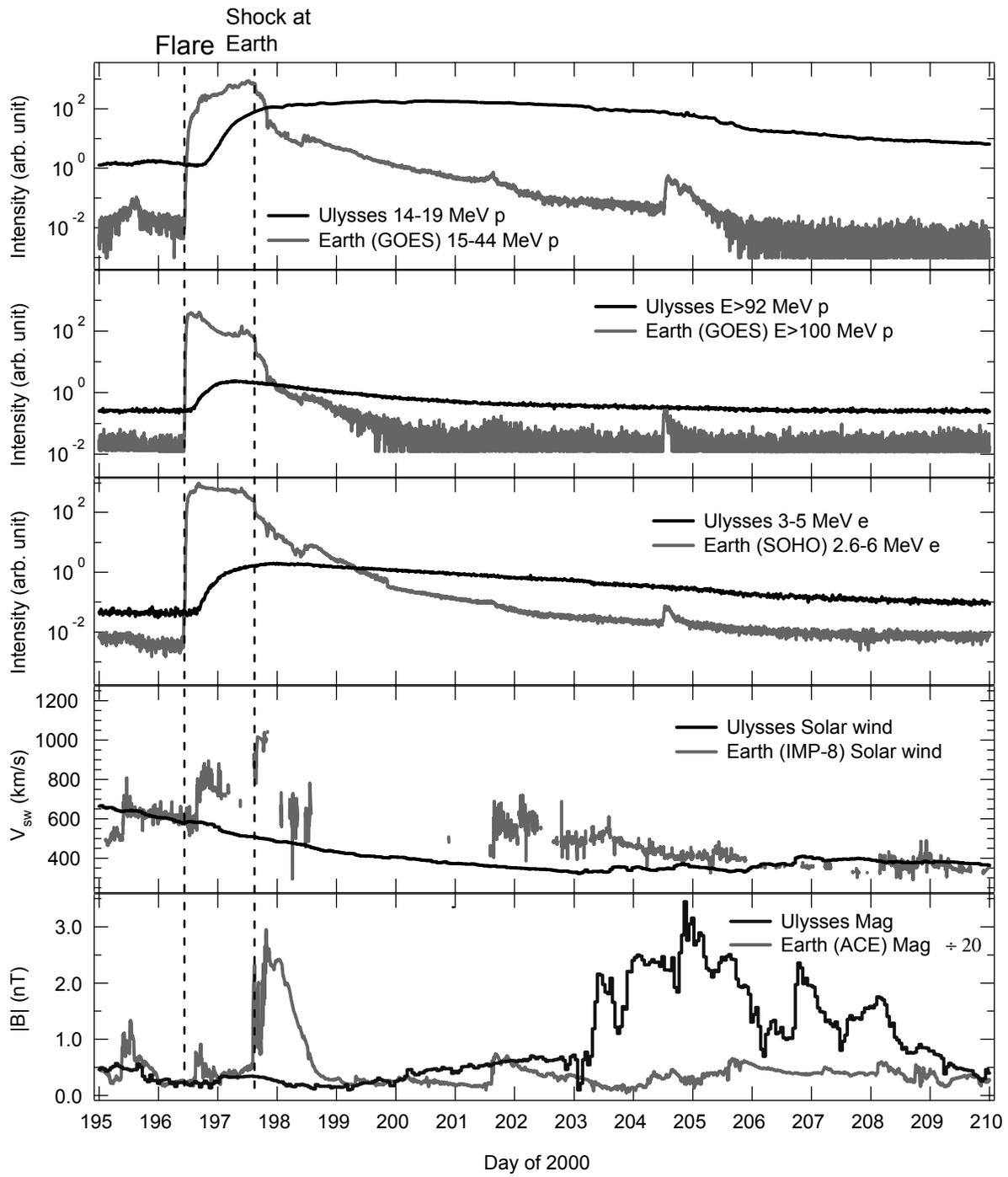


Fig. 2

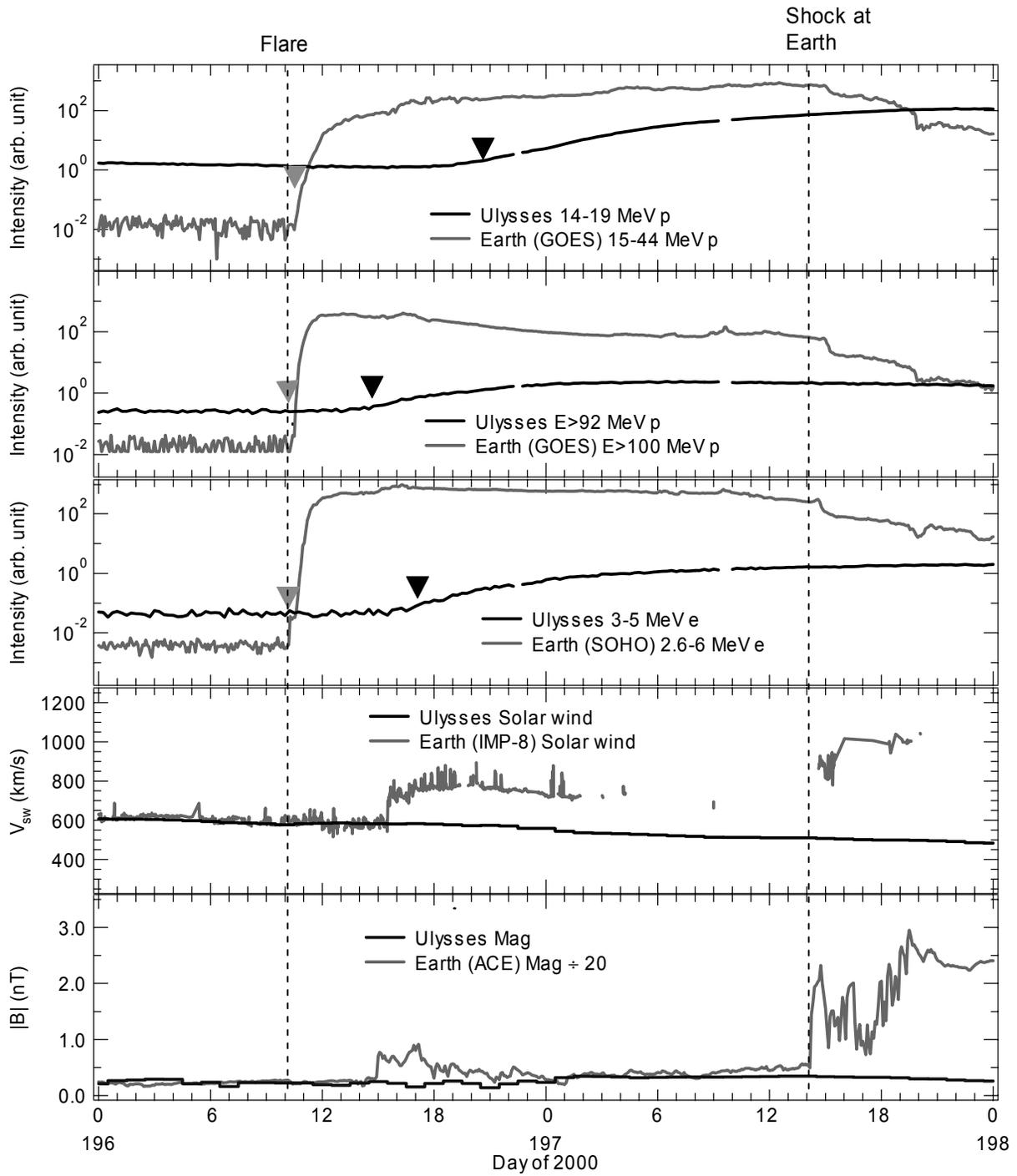


Fig. 3

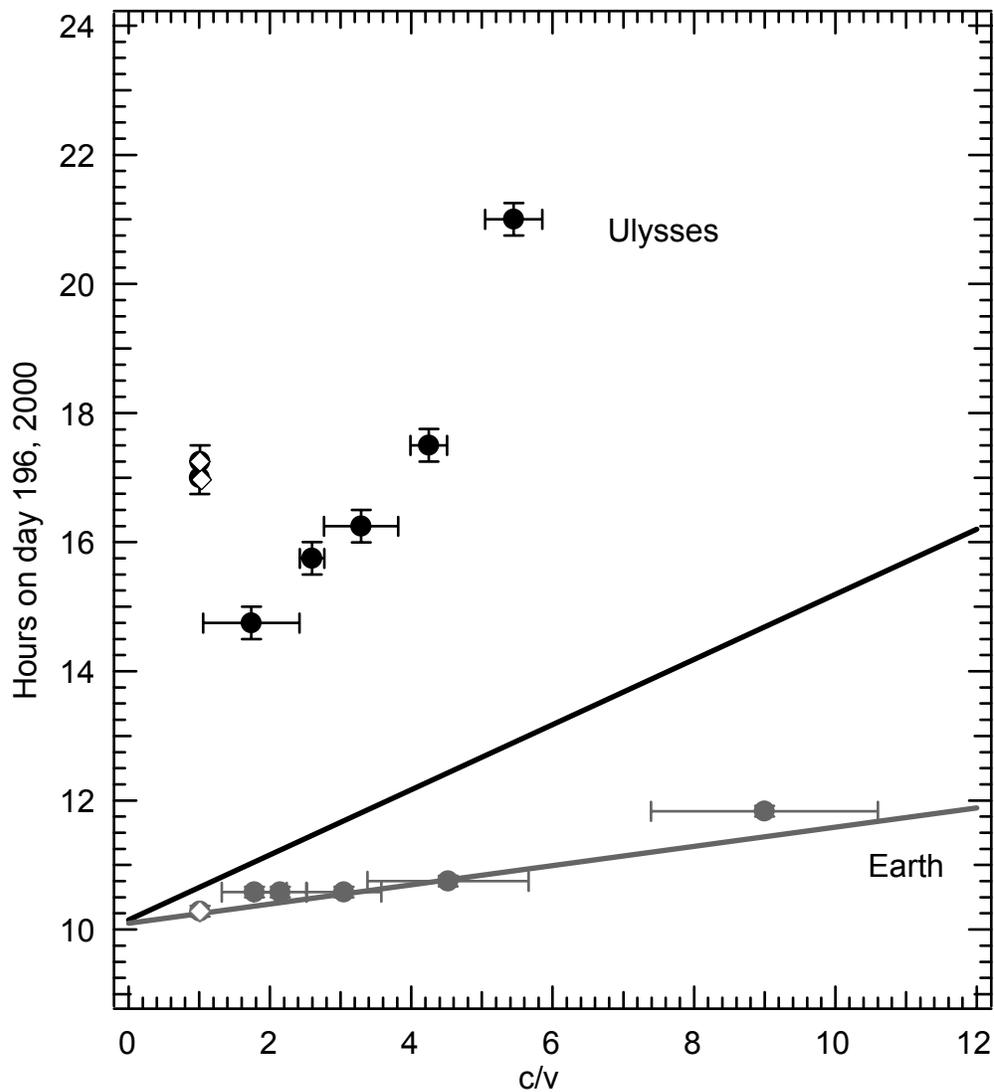


Fig. 4

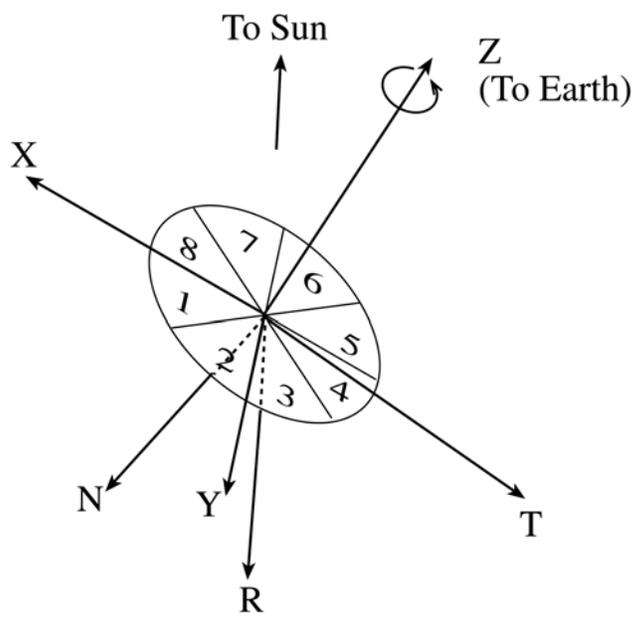


Fig. 5

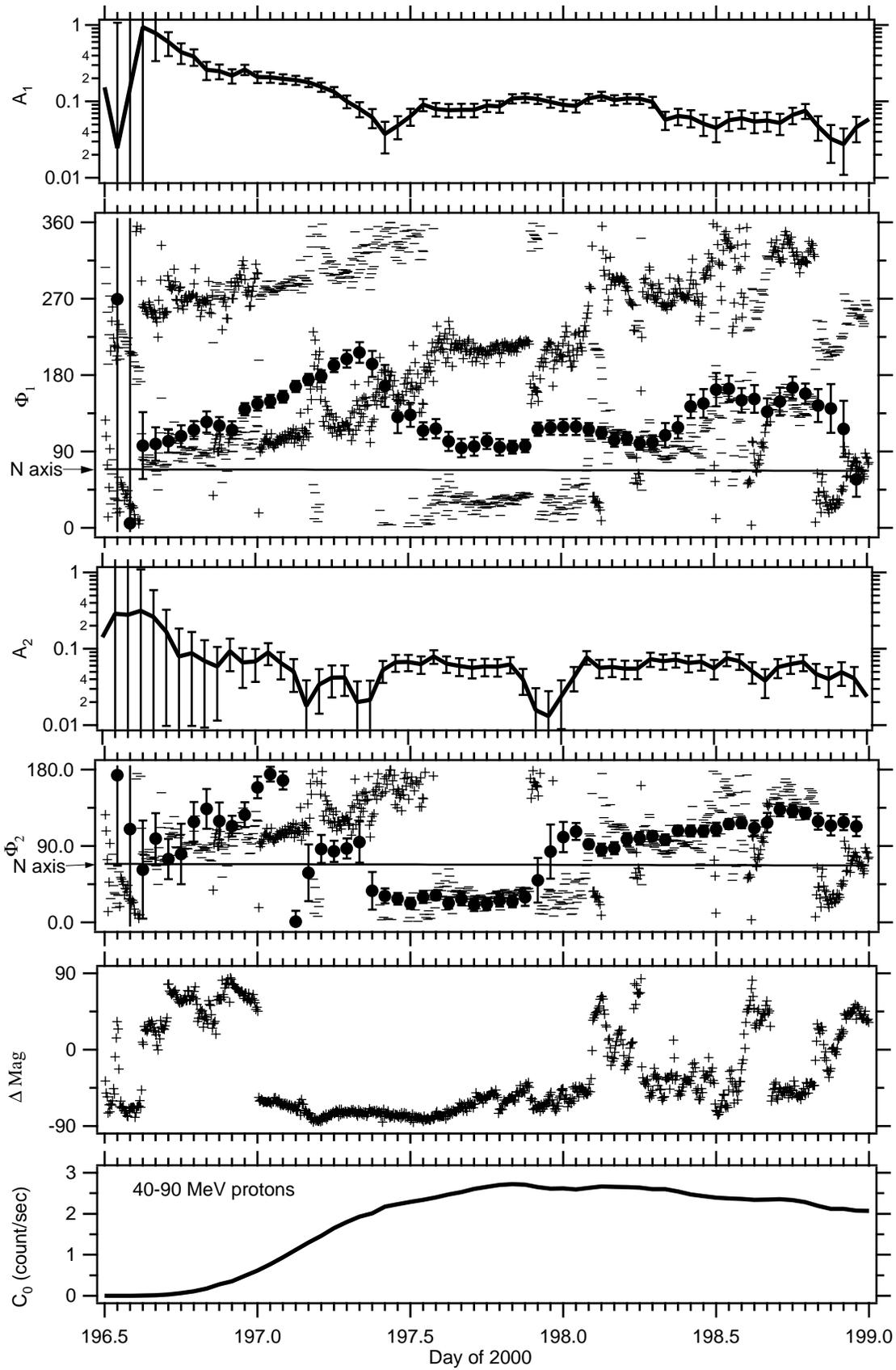


Fig. 6

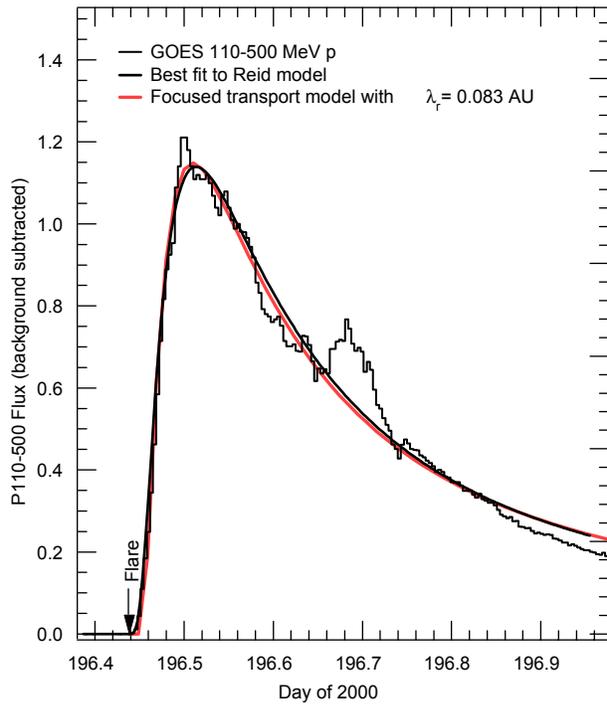


Fig. 7A

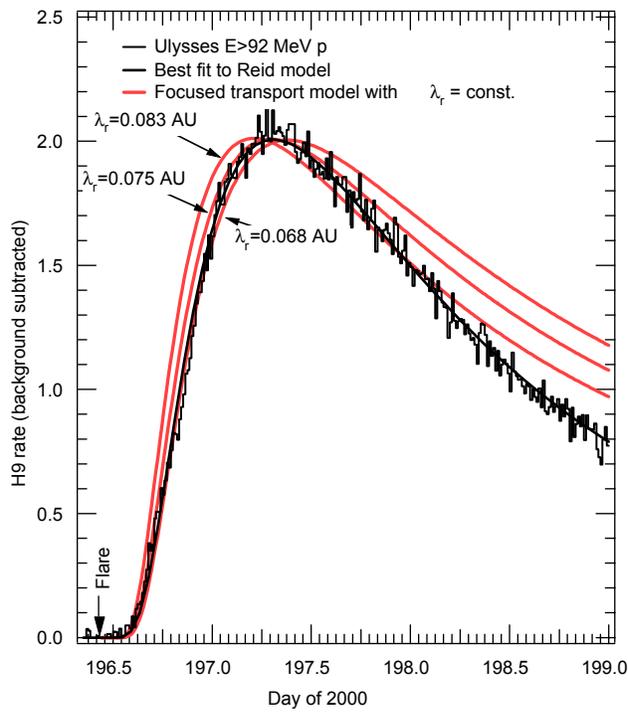


Fig. 7B

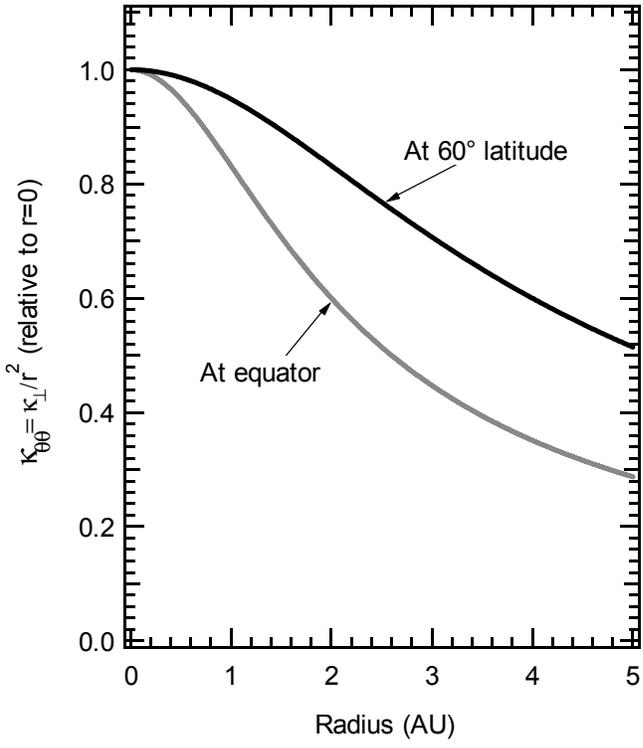


Fig. 8

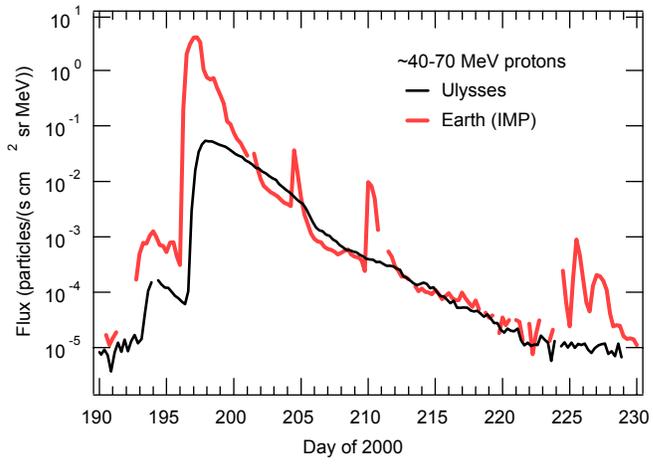


Fig. 9