North-south asymmetry of the location of the heliospheric current sheet revisited

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Received 3 July 2009; revised 9 September 2009; accepted 5 October 2009; published 27 January 2010.

[1] The possible latitudinal offset of the location of the heliospheric current sheet (HCS) is an important question, since it has impact on the understanding of various phenomena including the solar dynamo and the modulation of cosmic rays. In the declining phase of the previous, 22nd solar cycle, in 1993, a southward displacement of the HCS by 10° was proposed to explain the north-south asymmetry of energetic charged-particle fluxes measured by Ulysses. Other observations supported the north-south asymmetry as well, and it is now widely accepted by the scientific community that in 1993, the HCS was displaced 10° southward. However, in reality, the Ulysses magnetic field measurements did not give direct evidence for such a large displacement of the HCS. Here we revisit the question and extend our previous study for the declining phase of solar cycle 23 as well. Careful analysis of the HCS crossings observed by Ulysses during the fast latitude scans shows that a southward displacement of the HCS by 2°–3° is possible and consistent with the data for cycles 22 and 23. The impact of the HCS location on the latitudinal gradients of energetic particle fluxes is discussed.


1. Introduction

[2] The primary scientific objective of the Ulysses space probe, orbiting the Sun at high inclination angle with respect to the ecliptic, has been to make in situ observation of the various plasma, field, and particle parameters at different heliographic latitudes [Wenzel et al., 1992]. Launched in 1990, it has, to date, completed almost three orbits around the Sun. The orbital period is 6.2 years, close to half a solar activity cycle, well suited to observe the various states of the Sun between activity levels at comparable epochs. The characteristic properties of the heliosphere (solar wind and magnetic field parameters) evolve in time, primarily on the scale of the solar cycle. The changes through the solar cycle are themselves a function of, primarily, the heliolatitude of the observations. The so-called fast latitude scan sections of the Ulysses trajectory that occurred around the perihelion of the orbit are of particular importance, to study heliospheric structure as a function of heliolatitude, including any possible north-south asymmetry of the heliosphere. During the fast latitude scan the spacecraft travels from the South Pole to the North Pole in about a year; therefore, time variations associated with the solar cycle are expected to be minimal but may still not be completely negligible in certain respects.

[3] During the first fast latitude scan that occurred in the declining phase of solar cycle 22, in 1994–1995, Ulysses discovered a north-south asymmetry in the latitudinal gradient of the energetic particle fluxes [Simpson et al., 1996, Heber et al., 1996a, 1996b]. It was observed that the particle flux is roughly symmetric around a heliospheric latitude about 10° south rather than around the heliographic equator. The discovery has been interpreted as being due to a latitudinal offset of the heliospheric current sheet (HCS), by 10° to the south [Simpson et al., 1996]. Although a detailed examination of the Ulysses magnetic field measurements failed to prove such an offset of the HCS [Erdős and Balogh, 1998], the idea that the heliosphere was asymmetric, based primarily on the observation of an offset in the symmetry of the energetic particle gradients, has been widely accepted by the scientific community.

[4] The possibility that the heliosphere has a north-south asymmetry has attracted a considerable interest. Taking the subject in a more general context, such an asymmetry should originate from an asymmetry of the boundaries, i.e., either from the inner boundary (solar origin) or from the outer one (effect of the interstellar interface). Both possibilities are interesting. For the latter, the interstellar interface is clearly not symmetric (motion of the local interstellar cloud, direction of the interstellar magnetic field [see Pogorelov et al., 2009a]). That outer interface certainly influences the propagation of cosmic rays into the heliosphere, an effect that can be seen even close to the Sun although much reduced by modulation through the heliosphere. If the outer boundary introduced the asymmetry in the energetic particle intensities observed as an asymmetric latitudinal gradient (or rather one that is symmetric around a heliolatitude different from zero), then the asymmetry would not be seen in the solar wind and magnetic field properties, as these are related to their regions
of origin in the solar atmosphere. However, any north-south asymmetry in the solar wind or magnetic field would therefore suggest a solar origin, since a disturbance in the outer heliosphere cannot propagate to the inner heliosphere against the supersonic wind. There is, however, an effect that is related to the outer boundary that can influence the heliosphere: this is the effect of interstellar pickup ions on the solar wind [Gloeckler and Geiss, 2001]. A deflection of the interstellar hydrogen flow in the inner heliosphere by about 4°–5° with respect to the essentially nondeflected neutral helium flow was shown to exist by Lallement et al. [2005], although the effect of the pickup ions according to numerical simulations may be quite small [Pogorelov et al., 2009b].

[5] A solar origin of the north-south asymmetry of the HCS may have a large impact on theoretical models of solar magnetism, including dynamo and coronal models. A closely related near-Sun observation, that of nonradial streamers, was discussed by Wang [1996] before the Ulysses observations prompted a study of the possible causes of the asymmetry in the HCS. Coronal streamers are the near-Sun signatures of the coronal magnetic neutral line, and therefore, the systematic observation of nonradial streamers implies the possibility of a similar inclination of the HCS with respect to the coronal equator. Wang [1996] explained the nonradial geometry of the coronal streamers by the confinement of currents into thin sheets and relatively strong quadrupole and/or higher-order multipole terms in the photospheric magnetic field. The two related phenomena observed in the heliospheric medium, the possible asymmetry in the magnetic fields in the Northern and Southern hemispheres and the offset of the HCS, may be due to different but also related phenomena in the Sun’s magnetic state around solar minimum. Following Wang’s [1996] explanation for nonradial streamers, the asymmetry in the heliospheric magnetic field may be attributed to the evolution of the coronal magnetic quadrupole term. The offset, however, may be caused by an inclined “fossil” dipole term [Bravo and Gonzales-Esparza, 2000]. The possible presence of the latter field had been proposed by Bravo and Stewart [1995] to explain the wavy behavior of the heliomagnetic neutral line in the potential field version of the source surface models of the corona around solar minimum. Similar considerations concerning the solar and heliospheric asymmetry have been presented more recently by Mordvinov [2007]. A detailed assessment of the respective polarity areas on the coronal source surface model based on magnetograms obtained by the Wilcox Solar Observatory was carried out by Zhao et al. [2005], who concluded that the asymmetry at the source surface was consistent with the heliospheric results by Smith et al. [2000b].

[6] Evidence for the asymmetry in the heliosphere and the southward offset of the HCS have been interpreted jointly as evidence for a quadrupole moment and nonaxisymmetry in the solar dynamo by Mursula and Hiltula [2004]. The tilt of the solar magnetic dipole near the 1996 solar minimum (also covered by the first Ulysses fast scan in helioline) has been examined by Norton et al. [2008], using observations by the Solar and Heliospheric Observatory (SOHO) and Kitt Peak magnetograms. Their results are consistent with a relatively small (5°–10°) tilt of the HCS for that epoch. It can be envisaged that the asymmetry, as indeed the tilt of the solar dipole, may change with the solar cycle as well or even with the 22-year magnetic cycle (the Hale cycle).

[7] The Ulysses discovery of the asymmetry in the particle flux stimulated research for asymmetries in the magnetic field and plasma parameters. Those efforts included the Ulysses observation of the north-south asymmetry in the solar wind flow velocity, density, and temperature [McComas et al., 2000]. This study has found that there was only a small difference in solar wind speeds between south and north but larger differences in the mass flux; hence, the pressure of the solar wind was found to be greater in the south than in the north around the solar minimum in 1996. However, despite the apparently systematic differences in all the parameters, no statistically satisfactory quantitative conclusion could be reached, given the variability of the parameters, concerning asymmetries in the solar wind parameters between south and north. It appears that larger differences were more likely due to the evolving solar wind properties from the late declining phase to solar minimum. Solar wind composition measurements on Ulysses and the assessment of the implied temperatures of the northern and southern coronal holes have led Zhang et al. [2002] to conclude that there was a lasting asymmetry in the temperature and areas of the two coronal holes.

[8] Using the Operating Missions as a Node on the Internet (OMNI) magnetic field data set from 1964, which covers almost two 22-year Hale cycles, Mursula and Hiltula [2003] have shown a southward displacement of the average location of the HCS by a few degrees at solar minima, independent of magnetic polarity (i.e., in the same direction in both even or odd cycles). Northward displacement of the streamer belt at solar minimum of cycle 22 was observed by Mursula et al. [2002]; this is also supported by the Ulysses first fast latitude scan [Crooker et al., 1997].

[9] As mentioned earlier, a southward displacement of the HCS by Ulysses was discussed during the first fast latitude scan by Smith et al. [2000b]. In fact, the result, an apparent offset of ~10°, is largely backed only by in-ecliptic magnetic field measurements by the Wind spacecraft near the Earth, following the interpretation of the cosmic ray latitudinal gradient observations in terms of an asymmetry of the heliosphere, as indicated by the HCS. The arguments in favor of the large latitudinal offset of the HCS assumed time variations of the polar magnetic flux during Ulysses’s fast scan, which are not supported by direct observations in the Ulysses data. While it appears that both solar and indirect heliospheric data (cosmic ray latitudinal gradients and the magnetic sector ratios) indicate an offset of the HCS, the subject remains controversial because the extent to which these indicators have a unique explanation in the offset of the HCS is uncertain. We find it appropriate to revisit the question of the latitudinal offset of the HCS as measured by Ulysses, partly because other studies have extended the indirect observations of an asymmetrical HCS into previous solar cycles [Mursula and Hiltula, 2004; Mursula, 2007] and partly because now we have another two fast latitude scans by Ulysses, in 2001 and 2006, that provide extra opportunities to determine the latitudinal offsets and, in addition, to make comparisons between cycles 22 and 23.

2. Method of Data Analysis

[10] During fast scans from about 45° south to 45° north, Ulysses travels with a very nearly constant latitudinal
velocity of about 0.75°/d. This velocity is fast, considering that Ulysses therefore moves about 20° in heliolatitude during each solar rotation. On the other hand, the time taken by Ulysses from pole to pole is close to a year, during which time the solar conditions can evolve significantly. Nevertheless, the Ulysses orbit provides a good compromise that covers well the celestial sphere, corotating with the Sun, with a reasonably fine latitudinal resolution.

[11] From the solar wind velocity measured onboard, and knowing the position of Ulysses, we can calculate the theoretical Parker spiral of the magnetic field line intersecting the spacecraft. Projecting the measured magnetic field vector on the spiral gives a component that is pointing either away from or toward the Sun along the Parker spiral. This is taken to be the measure of the polarity of the magnetic field at the location of Ulysses. On average, the magnetic field has a well-defined positive, “away” polarity or a negative, “toward” polarity for intervals of several days or even a week or more, generating the characteristic two or four magnetic sector pattern that evolves from one solar rotation to the next [see Ness and Wilcox, 1964; Thomas and Smith, 1980; Bruno and Bavassano, 1997]. When measured at heliolatitudes poleward of the excursion of the HCS, the observations provide a uniform polarity that is the dominant polarity corresponding to the polar coronal hole, north or south, respectively, around solar minimum.

[12] Since we are interested in the solar origin of the heliospheric magnetic field, it is customary to map the observed quantities back to the Sun. This approach eliminates some relatively obvious variations connected to the orbital motion of Ulysses and offers a more direct comparison with solar/coronal models such as the source surface potential field model [see Wang and Sheeley, 1992, 1995; Hoeksema, 1995].

[13] When mapping back the observed characteristic of the magnetic field such as the magnetic polarity to the surface of the Sun, the solar wind travel time from its source to the point of observation needs to be taken into account. Normally, this is a simple procedure; radial expansion and inertial motion of the plasma are reasonably good and generally applicable approximations. The velocity of the solar wind is available from Ulysses measurements (courtesy of D. McComas; see Bame et al. [1992]). This results in a heliospheric longitude of the plasma source at the Sun, which is generally a decreasing function of the time of observation at Ulysses. An example for the solar longitude versus time of measurement function is shown in Figure 1, calculated from the position of Ulysses and from the solar wind velocity measured onboard for about a 2 month period in 2002, from 28 July to 13 August. If the position of Ulysses were fixed and if the solar wind velocity were stationary, then the heliolatitude of the plasma source would be a linear function of the time of observations at Ulysses; the relationship is therefore represented by a straight line parallel to the dashed lines shown in Figure 1. The slope of these lines is simply the equatorial angular velocity of the Sun, as Ulysses, being in an inertial orbit around the Sun, moves at about the solar rotation angular velocity with respect to the solar surface but in the opposite direction. However, as can be seen in Figure 1, there are significant deviations from the straight line because of the orbital motion of Ulysses and because of variations in the solar wind velocity. The effect of the orbital motion is small, as stated above. However, the radial velocity of the observer introduces a Doppler-type shift of the rotation rate of the Sun, which should be carefully corrected when north-south asymmetries are to be studied, because the radial velocity of Ulysses has opposite signs at the two hemispheres.

[14] Figure 1 shows that there are large deviations from the equatorial rotation rate due to fast wind–slow wind interactions. When a fast wind stream follows a slow-wind stream, a rarefaction region forms, and the corresponding longitude of the plasma source decreases rapidly in time. In contrast, when slow wind follows fast wind, the plasma source remains close to the same longitude for a time interval, called a dwell [Nolte et al., 1977]. It is customary to analyze the magnetic sectors by dividing the time series of the magnetic polarity in Carrington (or Bartels) rotation periods [see, e.g., Smith et al., 1986]. However, if we are interested to reconstruct the geometry of the current sheet, in particular to establish its north-south displacement or tilt angle, then we need to compare the longitudes that the opposite polarity sectors cover rather than comparing the times when they were observed. Figure 1 illustrates the danger of analyzing the data by the time of observations rather than by the longitude of the plasma source. The horizontal heavy lines (see the time scale on the top of Figure 1) mark the time intervals when positive magnetic polarity was observed, which covered 52% of the total time; that is, the dominant polarity seems positive. However, in reality, the dominant polarity was negative in this particular case because the longitude of the footprint of the magnetic field lines with positive polarity covered 46% of the total section only (see the vertical heavy lines at the right-hand scale). The uneven mapping of the time to longitude, as shown in Figure 1, is connected to variations in the solar wind speed. Because recurrent fast solar wind streams may be coupled with recurrent magnetic sectors in corotating interaction regions over several solar rotations a persistent and significant bias may be introduced in the positive-negative polarity ratios if the intervals are evaluated in terms of the
times of observations rather than in the corresponding solar longitude intervals.

There are extreme cases of dwells when the longitude versus time function becomes nonmonotonic. This is an unphysical situation, since the fast plasma will not overtake the slow one; therefore, the assumption of ballistic plasma trajectories is no longer valid. This case needs a much more sophisticated treatment, which involves MHD modeling. Single spacecraft measurements do not provide the necessary details of the boundary conditions for such a calculation; therefore, we have used a simple interpolation algorithm in order to avoid a multivalued function when mapping of the time of measurement to solar longitude. The inset in Figure 1 explains the algorithm, where first, the section of the multivalued part of the function should be identified (see the arrows). Then the section is replaced by linear interpolation. This simple procedure, although not very precise, mimics the stream-stream interaction and resolves the unphysical aspect of the calculated dwells. At the interface, the fast wind will slow down, and the slow wind will be accelerated; this results in a qualitatively similar distortion of the function as the linear interpolation used in these cases.


Equipped with all the necessary tools, we can construct the polarity of the heliospheric magnetic field at the Sun as measured by Ulysses during fast latitude scans. In Figure 2, the color code gives the magnetic polarity, with red and blue referring to outward and inward sectors, respectively. Note that intermediate colors on this “rainbow” scale, i.e., light blue, green, and yellow, are rare, backing the previous evidence that the measured magnetic field vectors follow the Parker field lines quite closely. The thick and color-coded lines show the trajectory of Ulysses in a frame corotating with the Sun’s equatorial rate. The position of Ulysses is mapped back to the Sun; the slight deviations from a “regular” spiraling line are due to the mapping procedure as discussed above. Earlier, Forsyth et al. [1996a] showed the three-dimensional map of the magnetic polarity observed during the first fast latitude scan in early 1995; this figure extends those observations to the second and third fast latitude scans. We can see that in 1995, corresponding to the declining phase of cycle 22, the northern polarity was positive; the southern polarity was negative; and the two hemispheres were separated by a moderately inclined current sheet. In 2001, at solar maximum, the inclination of the current sheet was large [Jones et al., 2003], and eventually, it flipped over at the time of the magnetic field reversal in 2000. In 2007, corresponding to the declining phase of cycle 23, the current sheet was again less inclined, in a way similar to the observations during the first fast latitude scan, but the polarity was reversed.

The calculation of the magnetic polarity at fast latitude scans, as shown in Figure 2, allows us to determine solid angles that the positive and negative polarities cover on the source surface. If the average location of the HCS is symmetric with respect to the equator of the Sun, then the area of the Northern and Southern hemispheres should be same. A more detailed test is the determination of the cumulative solid angle as follows [Erdős and Balogh, 1998]: Starting from the southern polar pass of Ulysses, we can integrate the step function, representing the magnetic polarity in equation (1a) by longitude and latitude along the trajectory of Ulysses in the frame corotating with the Sun with equatorial rotation rate (equation (1b)):

\[
S(\lambda, \Theta) = \begin{cases} 
-1 & \text{negative sector,} \\
+1 & \text{positive sector,}
\end{cases} \quad (1a)
\]

\[
A(\Theta) = \int_{S-pole}^{\Theta} \int_{0}^{2\pi} S(\lambda', \Theta') \cos(Q')d\lambda'd\Theta'. \quad (1b)
\]

This will provide a function of the time of observation and therefore of \(\theta\), which can be interpreted as the cumulative
The measure of the difference in the areas is compensated by different average magnitude of the Sun should be zero, the difference in the areas should be 0°. Since the total magnetic flux of the two magnetic polarities are not the same in the Northern and Southern hemispheres, the cumulative solid angle function as defined above for the first and third fast latitude scans in 1995 and 2007, a southern latitudinal offset of the current sheet by 2°–3° is possible. However, a southern latitudinal offset by as large as 10° seems inconsistent with our analysis, in agreement with our earlier study for the 1995 epoch [Erdős and Balogh, 1998].

The number of magnetic field lines with positive polarity should be strictly the same as that with negative polarity. Therefore, any latitudinal offset of the current sheet should be balanced with different averaged magnetic field strength in the Northern and Southern hemispheres. The magnetic field strength can be characterized by \( B_r \), which is the radial component of the field vector, normalized to 1 AU. Table 1 shows the normalized radial field averages measured by Ulysses during the first and third fast latitude scans (cycles 22 and 23, respectively). \( B_S \) is the southern magnetic field averages, measured from 80°S to 40°S. \( B_N \) is the magnetic field averages for the Northern Hemisphere. We can see that for the declining phases of both sunspot cycles, the magnetic field was slightly stronger in the Southern Hemisphere than in the Northern Hemisphere. The values of offsets in the HCS location are given that are necessary to compensate the stronger southern field in order to keep the positive and negative magnetic flux in balance. This calculation assumes that we can extrapolate the magnetic field strength measured at high latitude (greater than 40°, north or south) down to the current sheet. It is remarkable that the latitudinal offset values of the current sheet, determined from the balance of the magnetic flux (offset values in Table 1), are consistent with the offset values determined from the sector crossings of Ulysses (see Figure 3). One exemption is perhaps that a larger offset was obtained from the flux balance argument than from the cumulative area calculation for cycle 23, but the sign of the offset (i.e., to the south) was consistent in both cases.

Only the latitudinal offset during the first and third fast latitude scans have been discussed so far. The second fast latitude scan occurred during solar maximum conditions, in 2001. The observations coincided with the polarity reversal of the Sun [Jones et al., 2003]. As a consequence, the tilt of the current sheet was large, almost 90°, as we can see in Figure 2 (middle). In such a case, we cannot speak about the north-south displacement of the current sheet. However, the cumulative area function still can be determined. Analysis has shown that during the second fast latitude scan the area of the hemisphere with positive magnetic polarity was slightly larger than the one with...
Table 1. Radial Component of the Magnetic Field$^a$

<table>
<thead>
<tr>
<th>Cycle 22</th>
<th>Cycle 23</th>
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<tbody>
<tr>
<td>B$_x$</td>
<td>B$_y$</td>
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<tr>
<td>---------</td>
<td>---------</td>
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<tr>
<td>3.41 nT</td>
<td>3.05 nT</td>
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<tr>
<td>2.61 nT</td>
<td>2.16 nT</td>
</tr>
</tbody>
</table>

$^a$Normalized to 1 AU. Measured by Ulysses Between 40$^\circ$ and 80$^\circ$ latitude during the first and third fast latitude scans. Comparison of the Southern and Northern hemispheres and the corresponding latitudinal offset of the HCS, determined from the flux balance criteria.

... negative polarity. We could model the deviation with a few degree offset of the current sheet. However, time variations associated with the polarity reversal of the Sun, which happened during the time interval considered, make the interpretation of the offset difficult.

4. Discussion

[22] The Ulysses magnetic field observations during the first and third fast latitude scans, corresponding to the declining phase of cycles 22 and 23, have shown that the solid angles occupied by the positive and negative magnetic polarities on the solar wind source surface are almost the same. The small difference can be reproduced with the assumption of a southward displacement of the heliospheric current sheet by a few degrees. This latitudinal offset of the current sheet is also supported by the magnetic field observation of Ulysses at high latitude. According to that, stronger magnetic field was observed on the Southern Hemisphere than on the Northern Hemisphere. The argument is that the magnetic flux of the opposite polarities should be in balance; therefore, the north-south asymmetry of the magnetic field strength requires a displacement of the current sheet. Note that in both solar cycles analyzed, the displacement of the current sheet was in the same direction (i.e., southward), in spite of the opposite magnetic field configurations between the two adjacent solar cycles. The observations of Ulysses support the work of Mursula and Hiltula [2003], which showed the southward displacement of the heliospheric current sheet by a few degrees through several solar cycles.

[23] Ironically, the research of the north-south asymmetry of the location of HCS was largely motivated by the asymmetry observed in the latitudinal gradient of energetic particle fluxes. However, the observed displacement of the HCS is just a few degrees south, which does not give a convincing explanation for the particle data. The problem is that the apparent latitudinal asymmetry of the particle flux data is much more, about 10$^\circ$, than that of the HCS. A question, however, is as follows: What is the connection between the latitudinal gradient of the particle flux and the location of the current sheet?

[24] Answering the question needs the modeling of the transport of energetic particles through the heliosphere. This is an extensively studied subject [see, e.g., Heber and Potgieter, 2008, and references therein]; here, we give some arguments only explaining the main processes qualitatively. Considering drift motion effects, positively charged particles, detected by Ulysses during cycle 22, entered the heliosphere at the poles. As they moved toward Ulysses, they remained in the high-latitude regions, at least in the outer heliosphere. In the outer heliosphere, where most of the modulation is taking place, the observed particles did not cross the current sheet, which is limited to low latitudes at solar minimum. Therefore, the position of the current sheet was not likely to influence directly the flux of energetic protons or ions, observed by Ulysses close to the minimum of cycle 22. However, the offset of the HCS has an indirect effect on the modulation of particles through the magnitude of the magnetic field. As was discussed in the previous paragraph, the latitudinal offset of the HCS should be compensated by different radial component of the magnetic field in the Northern and Southern hemispheres. This would result in a different scattering mean free path of the particles in the two hemispheres, because of the difference in the gyroradii of ions. Note that according to most of the models, the scattering mean free path of energetic particles scales with their gyroradii.

[25] Simple considerations given above suggest that the latitude of the average position of the HCS is not necessarily identical with the symmetry point of the latitudinal gradient of particle fluxes, as had been suggested earlier to explain particle observations [see McKibben, 2001, and references therein]. This could explain why the latitudinal offset of HCS (2$^\circ$–3$^\circ$S) and the symmetry point of particle flux (10$^\circ$S) differ significantly. However, the offset of the HCS is quite small and makes it hard to develop models, resulting in a large latitudinal asymmetry in the particle flux. Earlier calculations used a latitudinal offset of the HCS as large as 10$^\circ$S, mostly inferring from models extrapolating the photospheric magnetic field observations to the source surface of the solar wind [Hookeema, 1995]. We would like to point out here that such a large offset of the current sheet is inconsistent with the Ulysses magnetic field observations.

[26] In order to explain any north-south asymmetry of the energetic particle fluxes, the relevant magnetic field observation is the radial component of the field close to the poles rather than the location of the current sheet. Ulysses was the only spacecraft to make measurements at the right place but possibly at the wrong time. Ulysses passed through the southern and northern polar regions about a half year earlier and later, respectively, than when the particle flux observation was carried out close to the equator. Ulysses did not measure a significant difference in radial component of the magnetic field at the poles [Forsyth et al., 1996a]. Smith et al. [2000a] have pointed out that time variation may be involved during the 1 year that elapsed between the two polar passes, and therefore, the magnetic field could have been different at the southern pole than at the northern pole while Ulysses was near the solar equator. This was supported by magnetic field observations by the Wind spacecraft, which obtained measurements at the right time but in the wrong place, i.e., in the ecliptic rather than at high latitude. Smith et al. [2000b] noticed the difference between the radial magnetic field measured by Wind in positive and negative magnetic sectors, and those values were extrapolated to high latitude (according to the magnetic cycle, the negative and positive sectors were extrapolated to the southern and northern poles, respectively).

[27] The question is, Which extrapolation is correct: the extrapolation in time (for Ulysses observations) or the extrapolation in heliographic latitude (for Wind observations)? Ulysses measured a time variation of the magnetic flux [Smith and Balogh, 2008] but on a large time scale corresponding to the 11 year solar cycle. Although variation on a shorter time scale cannot be totally excluded, the extrapolation in time
during the fast latitude scan appears to be correct. This suggests that the assumption of the significantly different magnetic field at the southern and northern poles while Ulysses crossed the equatorial region is not totally convincing. As for the extrapolation in latitude, in the fast solar wind, Ulysses did not observe significant variations in the magnetic flux by heliographic latitude [Forsyth et al., 1996a]; therefore, the extrapolation by latitude also looks correct. Smith [2007] explained the latitudinal independence of the magnetic flux by the superradial expansion of the solar wind close to the Sun. The idea is that the pressure of the magnetic field falls much more rapidly by radial distance from the Sun than that of the plasma. Therefore, in the region of a few solar radii, the magnetic pressure may dominate, resulting in non-radial plasma flow. An excess magnetic pressure at the high field regions can divert the plasma flow, which finally equalizes the magnetic flux at larger distances. This makes the extrapolation of the equatorial measurements by Wind up to the poles plausible. However, there is an inconsistency in this argument. If the non-radial solar wind expansion is sufficiently effective to equalize the magnetic pressure at all heliographic latitudes, then the magnetic pressure equilibrium should be applied to the two sides of the current sheet as well. However, this is not supported by even the Wind observations, which showed different magnetic fluxes in the opposite magnetic polarity sectors. Note that Ulysses measured the latitudinal independence of the magnetic flux at higher heliographic latitudes close to solar minimum (in both cycles 22 and 23), which corresponded to observations in the fast solar wind. In the slow solar wind, the magnetic flux has much larger fluctuations in time, making it difficult to study its latitudinal dependence.

[28] The hemispherical particle flux asymmetry could also be due to the asymmetric locations and areas of the polar coronal holes (or, somewhat equivalently, to the structure of the streamer belt) as proposed by Heber et al. [1998]. In addition, the overwinding of the heliospheric magnetic field in one hemisphere [Forsyth et al., 1996b] was considered by Heber and Burger [1999] as a potential alternative explanation. The consequences for the diffusion tensor due to the asymmetry of the heliospheric magnetic field with respect to the neutral line that would underlie the explanation of asymmetric particle fluxes were examined by Hattingh et al. [1997].

[29] As a conclusion, magnetic field observations by Ulysses did not give clear evidence and clear explanation for the asymmetry of the latitudinal gradient of energetic particles observed by Ulysses during the first fast latitude scan in 1995 in terms of a southward displacement of the heliospheric current sheet. One remark is that the reality of the observation in the latitudinal asymmetry of the particle flux might also be questioned as perhaps due to a temporal evolution suggested by Heber et al. [1998]. For the same reason as was argued by Smith et al. [2000b] that time variation during the fast latitude scan could be involved in the magnetic field measurement, we may also consider that time variation of similar extent in the particle flux, coupled with the latitudinal motion of Ulysses, would result in spurious latitudinal asymmetry in the particle flux observations.

[30] An interesting finding of the magnetic field observation of Ulysses is that the areas of positive and negative polarity sectors on the solar wind source surface tend to be closely equal. This can be explained as follows: at small radial distances from the Sun, the solar wind flow may be diverted from the radial one by magnetic pressure, which results in a quasi-equal magnetic field line density at larger distances. However, for both cycles 22 and 23, a slight but persistent southward displacement of the current sheet by a few degrees and a corresponding slightly stronger magnetic field at the South Pole than at the North Pole is consistent with the magnetic field observation of Ulysses. If further investigations confirm this small north-south asymmetry, the explanation would be a challenge for solar physicists.

[31] Acknowledgments. Part of this work was carried out while G.E. was a guest of the International Space Science Institute, Bern, Switzerland. The research was partly supported by Hungarian Science Fund OTKA K-62617.

[32] Amitava Bhattacharjee thanks Bernd Heber and Nikolai Pogorelov for their assistance in evaluating this paper.

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