Asymmetry of solar polar fields and the southward shift of HCS observed by Ulysses

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[1] We study the hemispheric asymmetry of high-latitude unipolar fields and the latitudinal shift of the heliospheric current sheet (HCS) using Ulysses magnetic field observations during the perihelion passes in 1994–1995, 2001–2002, and 2007. Using the cumulative flux density and the best fit lines to its high-latitude observations in the two hemispheres, we find that the absolute value of the high-latitude radial field of the Southern Hemisphere is larger than in the north during both minimum time scans in 1994–1995 and 2007. The hemispheric difference is about 0.2 nT during both scans, suggesting that the northern field area is some 5%–10% (5%–15%) larger than the southern area and that the HCS is shifted southward by about −2° during both scans. The results resolve the discrepancy between earlier results in 1994–1995 and clarify similar observations in 2007 in the ecliptic. They also verify the southward shift of the HCS during the exceptional solar cycle 23. We also study the detailed structure of the equatorial region and find that generally the Ulysses observations compare favorably with simultaneous heliospheric magnetic field predictions given by Wilcox Solar Observatory synoptic maps. Using a simple HCS model, we find that even in case of southward shifted HCS, the highest peak of the cumulative flux density could be located above the equator. Thus, Ulysses observations around the heliographic equator cannot alone give an unambiguous information of the HCS shift, which emphasizes the importance of studying the high-latitude sections of Ulysses orbit.

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1. Introduction

[2] The heliospheric current sheet (HCS) is the continuation of the solar magnetic equator from the corona into the heliosphere. Accordingly, the HCS is an important element of the global magnetic field of the Sun, and its structure experiences dramatic changes over the solar activity cycle. An interesting new observation was made during the first fast latitude (perihelion) scan of the Ulysses probe [*Simpson et al.*, 1996; *Crooker et al.*, 1997; *Smith et al.*, 2000] that the HCS was southward shifted at that time in the late declining phase of solar cycle (SC) 22. The structure of the HCS in this situation was lucidly illustrated in Figure 6 of *Smith et al.* [2000]. It was subsequently shown using OMNI data that this southward shift, also called the bashful ballerina, has occurred in the late declining phase of all solar cycles of the space age [*Mursula and Hiltula*, 2003] and even in earlier decades since solar cycle 16 [*Hiltula and Mursula*, 2006]. *Zhao et al.* [2005] verified, using the heliospheric magnetic field (HMF) predicted by the measurements of the photospheric field at the Wilcox Solar Observatory (WSO) and the potential field source surface (PFSS) model [*Altschuler and Newkirk*, 1969; *Schatten et al.*, 1969], that the HCS was indeed shifted southward during SC 21 and SC 22 and that the northern field is, accordingly, slightly weaker.

[3] However, our latest results obtained by comparing OMNI data collected in the ecliptic and WSO observations show that during the declining phase of SC 23 the latitudinal ordering of the heliospheric magnetic field and the related HCS asymmetry are exceptionally weak [*Mursula and Virtanen*, 2010]. This was suggested to be related to the exceptionally weak polar fields during the declining phase of SC 23 [*Smith and Balogh*, 2008] when the HCS has a relatively larger dipole tilt angle, which also implies a larger latitude extent of the HCS, than during the similar times of previous recent solar cycles.

[4] In addition to the above mentioned studies concentrating on the first perihelion scan, Ulysses observations have been used to study the hemispheric asymmetry of the heliospheric magnetic field more generally. It was found by *Forsyth et al.* [1996] that the field was, on an average, slightly weaker in the Northern Hemisphere than in the south. This is in a very good agreement with the larger area and weaker field in the Northern Hemisphere and the related southward shifted HCS. The ratio of the northern to southern field was

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about 0.95 which would correspond to a southward shift of HCS by about 3°. However, the statistical significance of the difference was not very strong, only about 2.5 standard deviations, rendering this result as inconclusive. Subsequently, *Erdös and Balogh* [1998] studied the hemispheric asymmetry during the first perihelion scan of Ulysses and found that the coronal source areas of the Northern and Southern Hemispheres were equal, in contradiction to all the above results of hemispheric asymmetry and HCS shift at this time [*Simpson et al.*, 1996; *Forsyth et al.*, 1996; *Crooker et al.*, 1997; *Mursula and Hiltula*, 2003]. During the review process of this paper a revised paper by *Erdös and Balogh* [2010] was published which corrects the results of *Erdös and Balogh* [1998], verifying a southward shift for the first fast latitude scan.

[5] In this paper we reanalyze the hemispheric asymmetry of the heliospheric current sheet using Ulysses magnetic field measurements during the first fast latitude scan in 1994–1995, and continue the analysis to the second and third perihelion scans in 2001–2002 and in 2007. Only perihelion scans are considered here because they last less than a year while the slower aphelion scans take about 5 years. During the 5 year aphelion scan the field suffers a large change due to the solar cycle. Also, the aphelion scan is longer than the 3 year interval of uniform hemispheric asymmetry [*Zhao et al.*, 2005], limiting the possibility of systematic observations. We calculate the cumulative flux density from the radial component of the magnetic field (scaled by r^2 to 1 AU) observed by Ulysses, and estimate the latitudinal location of the HCS. The paper is organized as follows. Section 2 presents the Ulysses data to be used, and section 3 gives the overall view of the heliospheric magnetic field observed by Ulysses. Section 4 discusses the asymmetry of the high-latitude fields, and section 5 studies the corresponding hemispheric areas and the HCS shift. Section 6 gives the detailed view of the heliospheric magnetic field around the equator, and section 7 compares the Ulysses results with WSO coronal maps. Section 8 presents our conclusions.

2. Data

[6] We use here Ulysses' measurements of the heliospheric magnetic field at hourly resolution. During its lifetime in 1992–2008 the probe completed three orbits around the Sun in a roughly polar orbit. The orbit perihelion (aphelion) is located in the solar equatorial plane at the distance of about 1.3 AU (5.4 AU).

[7] Having the highest speed at the perihelion, Ulysses crosses 19.9° of heliographic latitude during one sidereal 25.38 day solar rotation. If we take into account that during one sidereal solar rotation the heliographic (HGI, heliographic inertial) longitude of Ulysses increases by 3.5°, one rotation observed by Ulysses (synodic rotation period in Ulysses coordinate system) takes 25.63 days. During this period Ulysses crosses almost exactly 20.0° of latitude.

[8] At the perihelion the latitude changes roughly linearly with time, but at higher latitudes linearity is no longer valid. In order to have the flux density sampled equally in latitude over the whole scan from south pole to north pole, we calculate the average of the scaled B_r inside 0.1° latitude bins, not per time unit. Then the calculated cumulative flux density will change linearly with latitude over the whole latitude range, yielding a homogeneous data series, which is important when calculating the cumulative flux density. In addition, this procedure also removes the remaining small data gaps.

[9] Note that the first perihelion scan took place at a time when the hemispheric asymmetry was observed to be systematic and fairly large also by OMNI [*Mursula and Hiltula*, 2003] and WSO observations [*Zhao et al.*, 2005]. On the other hand, despite occurring during a solar minimum time, only a small asymmetry was found in OMNI and WSO data during the third perihelion scan [*Mursula and Virtanen*, 2010]. The second scan occurred during the solar maximum time, when no systematic asymmetry exists.

[10] Figure 1 presents the values of B_r (flux density) within 0.1° latitude bins during the three Ulysses perihelion scans. Values are normalized to 1 AU expecting that $B_r r^2$ remains constant with distance. The average magnitude of the high-latitude field is considerably reduced between the first and third scan from 1994–1995 to 2007 [see, e.g., *Smith and Balogh*, 2008]. The HMF follows a mainly dipolar structure (opposite unipolar fields around the two poles) during the first and third scans in the late declining phase of SC 22 and 23, although some data points with opposite polarity are observed even at very high latitudes. As earlier found [*Smith and Balogh*, 1995] the absolute value of B_r is mostly independent of latitude, but the largest values in minimum time conditions are observed inside the HCS region, within about 30° of latitude due to the interaction of fast and slow solar wind streams.

[11] During the second scan in 2000–2001 in solar maximum time the radial HMF oscillates, because of the large tilt angle, quite systematically at all latitudes at the Ulysses synodic solar rotation period of 25.63 days, i.e., at multiples of 20° of latitude based on Ulysses' latitudinal rate of change. However, during the minimum time scans, the variation in the HCS belt region, where both polarities are observed, is more complicated. In 1994–1995 the dominant oscillation period is shorter, about 10°, i.e., roughly half the synodic rotation period, indicating a dominant four-sector structure at this time. The largest peak values during this scan are located within 20° of equator. In 2007 the current sheet region of large oscillations is somewhat wider, about 30°, and the dominant period is the synodic rotation with a subdominant oscillation at half shorter period.

[12] In addition to Ulysses magnetic field data, we will also use here Wilcox Solar Observatory synodic maps that are based on photospheric field measurements and the PFSS model. We use the WSO maps with the source surface at the distance of 2.5 solar radius.

3. Overall View

[13] We calculate the cumulative flux density at the HGI latitude θ as follows:

$$\Phi_c(\theta) = \sum_{\theta'=\theta_s}^{\theta} B_r r^2(\theta'), \qquad (1)$$

where $\theta_s = -79.7°$ is the southernmost latitude where the summing starts (the highest latitudes are ±80.2° for the first two scans and ±79.7° for the third scan) and the sums are

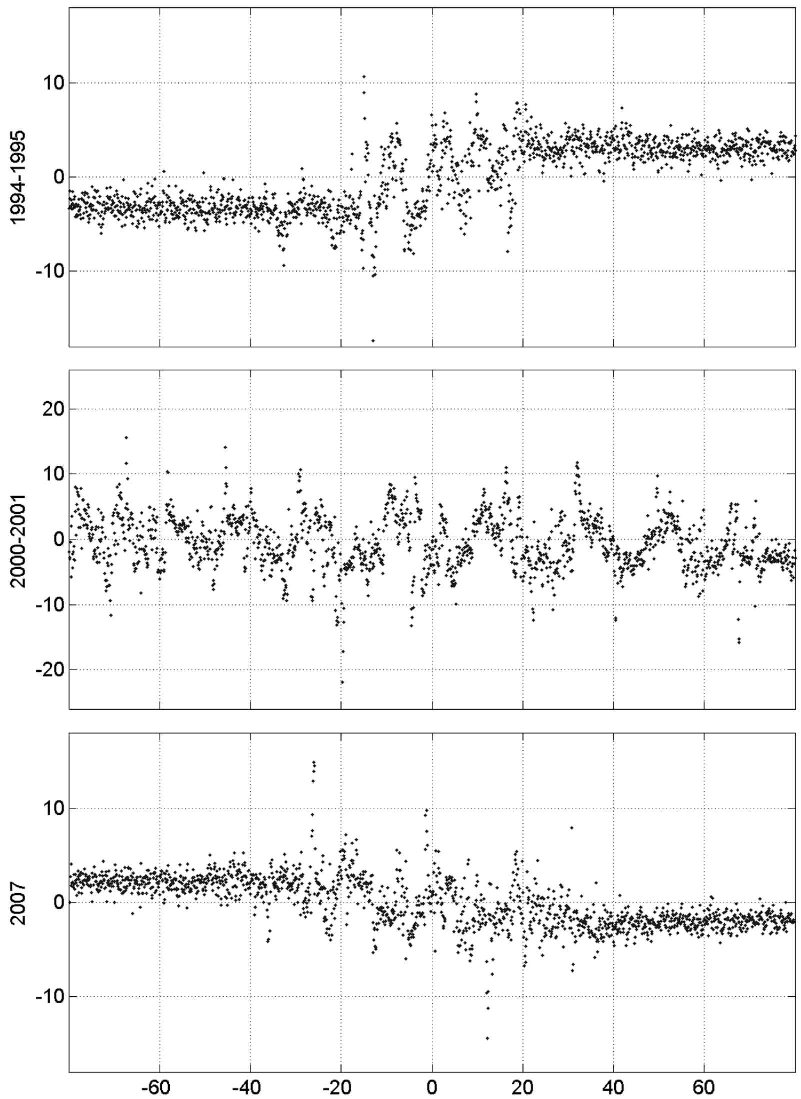

Figure 1. The 0.1° latitude bin values of the r^2-scaled radial field B_r (in nT) for the three Ulysses fast latitude scans.

taken over the 0.1° latitude bins. Here the distance r is given in units of AU, which means that we have scaled the field to 1 AU expecting that the radial component decreases like $1/r^2$.

[14] Cumulative flux densities for the three Ulysses perihelion scans are presented in Figure 2. During the first scan the flux density decreases toward the equator almost linearly with latitude and then, after crossing the equatorial region, increases toward the north pole. This reflects the fact that the magnetic field is unipolar and nearly latitude independent over an extensive range of latitudes in either hemisphere [*Smith and Balogh*, 1995]. The peak value of the cumulative flux density (either a minimum as in 1994–1995 or a maximum as in 2007) is observed around the equator in the HCS region.

[15] Figure 2 shows that the overall configuration of HMF in 2007 was also dipolar with an opposite orientation of the solar polarity compared to 1994–1995. However, the equatorial HCS region in 2007 was spread over a larger range of latitudes than in 1994–1995. Note that the peak value of the cumulative flux density gives a rough, first-order estimate of the total magnetic flux of the Sun. Accordingly, Figure 2 shows clearly that the highest peak of the cumulative flux density, i.e., the flux density maximum in 2007 is only about 56% of the (absolute value of the) flux density minimum in 1994–1995 [*Smith and Balogh*, 2008].

[16] Figure 2 also depicts a very different HMF structure during the second perihelion scan in 2000–2001 around the solar maximum of SC 23 when the polar field was weak and reversing polarity. Perhaps slightly surprisingly, the flux density at high southern latitudes first slowly increases toward the equator, indicating an early dominance of the new polarity around the southern pole. However, the flux reversed at about −40°, suggesting that there were still large regions of the old, negative polarity at midlatitudes and low latitudes of the Southern Hemisphere. Around and above the equator until about +60°, the flux density depicts large oscillations every 20° of latitude corresponding to the synodic solar

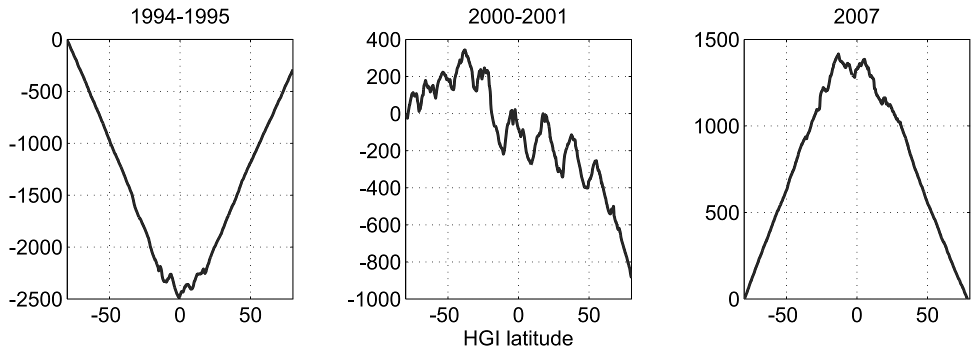

Figure 2. Cumulative flux density as a function of heliographic latitude from −79.7° latitude toward the equator for the three Ulysses fast latitude scans. Constant slope indicates a uniform flux density. Note that the scales are quite different in each panel.

rotation period. When Ulysses reaches about +60° the high-latitude field in the north has already developed to a unipolar structure typical for the minimum time configuration. Note also that, because of the many regions of opposite polarity, the peak cumulative flux density observed during the second scan remains significantly below the peaks of the two minimum time scans.

4. Asymmetry of the High-Latitude Fields

[17] Let us now consider the slopes of the cumulative flux density curves at high latitudes. As mentioned above, the cumulative flux density is linearly proportional to latitude if B_r remains constant (in latitude and time). This means that, under this assumption, the slope of the cumulative flux density curve in unipolar regions will give the average value of the local B_r. Therefore, in order to study the radial field intensities in the two hemispheres, we will fit a line to the cumulative flux density curves in the Northern and Southern Hemispheres separately, and find the corresponding slopes k_N and k_S. Figure 3 presents the cumulative flux density in 2007 and the best fit lines to its northern and southern high-latitude sections. The lines in Figure 3 correspond to a fit from ±79.7° to ±14°. Figure 3 shows that the northern and southern lines intersect below the equator, indicating that the northern slope, i.e., the northern radial field, is weaker than the southern field, and implying a southward offset of the equatorial HCS belt region.

[18] In Figure 3 the 14° equatorial limit of the fitting range was selected as a typical width of the equatorial HCS region at this time. However, this limit of the fitting range is basically a free parameter, and reliable field estimates should not be sensitive to its exact value. Accordingly, we have examined how the hemispheric slopes and the associated HCS asymmetry change when varying this limit. Figure 4 presents the slopes of the best fit lines in the two hemispheres in 1994–1995, 2000–2001 and 2007 as a function of the equatorial limit of the fitting range.

[19] In 1994–1995 typical values of the radial field intensities are about 3 nT or somewhat larger. While the northern slope remains rather constant with fitting range limit, the southern slope slightly increases (roughly by 10%) when the fitting range expands toward the equator. The latter is probably due to the temporal development with the southern polar field intensity still increasing during Ulysses pass. Figure 4 shows that the absolute value of the slope of the Southern Hemisphere is systematically larger than in the north for all values of the fitting range limit. This shows that the radial field in the south is about 0.2 nT larger than in the north during this pass. (Note also that the above mentioned temporal development tends to underestimate this difference. A more developed southern pole would further raise the southern slope.)

[20] In 2000–2001 the southern slope is very weak and almost independent of the fitting range until about 13°, when it turns negative, in agreement with the cumulative flux

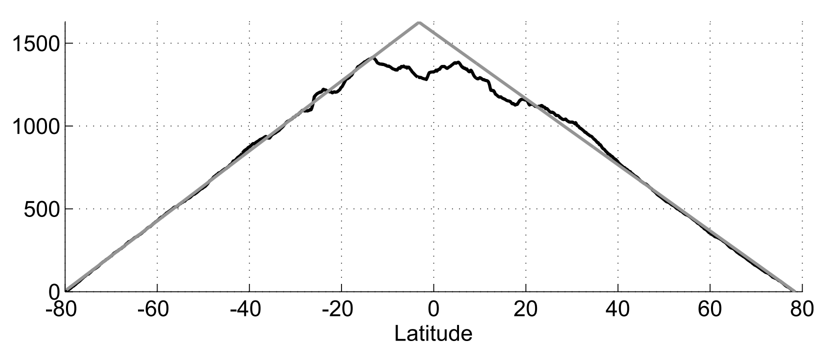

Figure 3. Best fit lines (solid gray lines) for the cumulative flux density in the Northern and Southern Hemispheres in 2007. Fits are made using values between ±79.7° and ±14°, which is a typical minimum time range for uniform B_r.

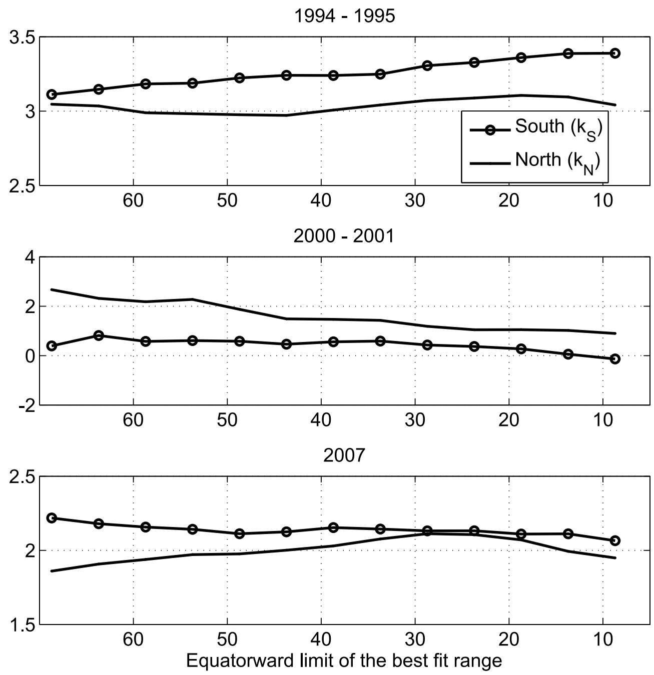

Figure 4. Best fit line slopes for the cumulative flux density curves in the Northern and Southern (denoted by open circles) Hemispheres as a function of the equatorial limit of the fitting range. Slopes give the average B_r within the fitting range. For presentation, the sign of the southern (northern) field was changed in 1994–1995 (2000–2001 and 2007). The fitting range starts from ±79.7° on each pass and extends to the latitude indicated on the abscissa. Note the different scale in Figure 4 (middle).

density curve depicted in Figure 2. The northern slope (field) is clearly larger because the unipolar region of the new polarity already covers a large range of high northern latitudes by the end of the fast latitude scan (see also Figure 2, middle). However, the northern slope is decreasing with the summing range in Figure 4 because the earlier passed mid-latitudes still contain mixed polarity regions while in the highest latitudes, where data were taken latest in time, the field was already fairly unipolar. Note that the field intensity at the highest northern latitudes in 2001 is only slightly smaller than its value during the previous minimum in 1995. Accordingly, the reduction of the (northern) polar coronal field intensity observed between the first and third perihelion scans mainly occurred only after the second Ulysses pass in early 2001. This supports the recent note of a dramatic change in the solar magnetic field in 2001/2002 [*Lukianova and Mursula*, 2010] (note also that the difference between the two slopes in 2000–2001 is due to the temporal evolution of the field over the solar cycle, and does not reflect the difference between the two large unipolar regions as in 1994–1995).

[21] Figure 4 (bottom) shows that in 2007 the two slopes (fields) are considerably smaller than in 1994–1995, in agreement with the weaker polar fields [*Smith and Balogh*, 2008]. The southern slope slightly decreases and the northern slope increases toward the equator because the polar coronal holes develop very slowly during SC 23 and are smaller than, e.g., in SC 22 [*Harvey and Recely*, 2002; *Kirk et al.*, 2009]. Moreover, low-latitude coronal holes, which are typical for solar maximum times, still occurred in the late declining phase of SC 23 [*Gibson et al.*, 2009], demonstrating the exceptional nature of SC 23. Because of the low-latitude coronal holes, the strong latitudinal organization of the field typical for solar minima is delayed in SC 23 [*Mursula and Virtanen*, 2010]. This is also related to the large tilt angles at this time, leading to an excessively wide HCS region with almost equal amounts of either field polarity. Accordingly, the slopes equatorward from about 40° in both hemispheres do not correspond to field values in the unipolar regions and should not be used when studying the hemispheric asymmetry of unipolar regions.

5. Areas of the Two Polarities and the HCS Shift

[22] Figure 4 verifies that the magnitude of the radial field in the southern unipolar region is larger than the field in the northern pole during both minimum time fast latitude scans. By flux conservation, this leads to the fact that the northern field must encompass a larger solid angle than the southern field. As a consequence then, the heliospheric current sheet will be shifted southward at these times. In this section we now study the areas and the HCS shift in more detail.

[23] According to flux conservation, the total fluxes of northern and southern polarity must be the same, $\Phi_N = \Phi_S$. If the northern polarity field covers an area A_N and the southern polarity field an area A_S, it must be that $A_N B_{r,N} = A_S B_{r,S}$. Using this relation and the values of slopes depicted in Figure 4 we find that the northern field area is some 5%–10% (5%–15%) larger than the southern area in 1994–1995 (in 2007). For the first perihelion scan, this result is in good agreement with several earlier results [*Simpson et al.*, 1996; *Forsyth et al.*, 1996; *Crooker et al.*, 1997; *Mursula and Hiltula*, 2003], and the recent revision by *Erdös and Balogh* [2010] which corrects the earlier result by *Erdös and Balogh* [1998] of no asymmetry.

[24] During the third perihelion scan in 2007, the smaller flux density and larger area in the north shows that the asymmetry of the high-latitude unipolar regions in SC 23 was oriented in same direction and roughly by the same amount as in several earlier cycles [*Mursula and Hiltula*, 2003; *Hiltula and Mursula*, 2006], despite the particular nature of SC 23. This clarifies the recent finding [*Mursula and Virtanen*, 2010] that inferred a very small asymmetry seen at the ecliptic, and shows that using ecliptic observations during a weak cycle like SC 23 one cannot easily study the properties of the (reduced) unipolar areas because the strong latitudinal organization of the field is not established sufficiently well at those rather low heliographic latitudes reached by the Earth's orbit at the ecliptic.

[25] Taking into account that the slopes give the local B_r and the fact that $A_N + A_S = 4\pi R^2$ we can find

$$A_N\left(1+\frac{k_S}{k_N}\right) = 4\pi R^2, \tag{2}$$

where R is the radius (the satellite orbit or distance 1 AU). On the other hand, making the simplifying assumption of

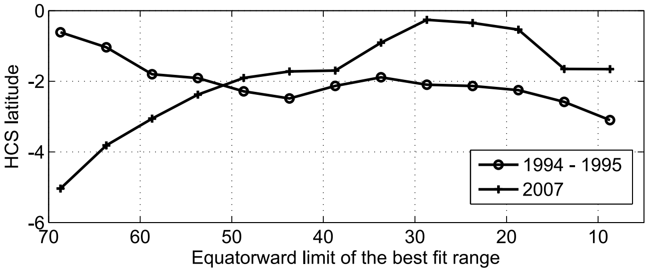

Figure 5. Longitudinally averaged heliographic latitude of the heliospheric current sheet in 1994–1995 (denoted by open circles) and in 2007 (denoted by vertical ticks) as a function of the extent of the fitting range.

longitudinal symmetry (flat HCS), we can integrate the area covered by the northern polarity as follows:

$$A_N = \int_0^{2\pi} \int_0^{\theta_m} R^2 \sin\theta d\theta d\phi = 2\pi R^2 (1 - \cos\theta_m), \tag{3}$$

where θ_m is the angle between the north pole and the magnetic equator (magnetic colatitude). Solving the magnetic latitude $\lambda_m = \frac{\pi}{2} - \theta_m$ from equations (2) and (3) we get

$$\lambda_m = \sin^{-1}\left(\frac{k_N - k_S}{k_N + k_S}\right). \tag{4}$$

Accordingly, equation (4) gives the (longitudinally averaged) latitude of the solar magnetic equator, i.e., the heliospheric current sheet, in terms of the field magnitudes of two unipolar regions. Figure 5 depicts the HGI latitude of the heliospheric current sheet obtained from the northern and southern slopes measured in 1994–1995 and 2007 (see Figure 4), in terms of the extent of the fitting range. Figure 5 verifies that the average HCS latitude is negative, i.e., that the heliospheric current sheet is southward shifted during both minimum time perihelion scans.

[26] In 1994–1995 the estimated southward shift of the HCS is almost independent of the fitting range because the slope difference remains fairly constant (see Figure 4). However, as discussed above, because of the still developing southern polar coronal hole in 1994, the more correct slope values in 1994–1995 are obtained from midlatitudes (about 20°–60°), and the most reliable estimate for the HCS asymmetry in 1994–1995 is about −2°. On the other hand, as mentioned above, the situation is very different in 2007, and the estimates below 40° must be ruled out. Accordingly, the most reliable estimate of the HCS shift in 2007, about −2°, is obtained as an average from latitudes of about 40°–60°. Note that the absolute intensities of the radial field in 2007 are smaller than in 1994–1995, but the HCS shift depends only on the relative field difference (see equation (4)). Therefore, even a smaller difference between the southern and northern fields (about 0.13 nT) in 2007 gives a roughly equal shift in 2007 as in 1994–1995. We note that this equality may, in fact, reflect some deeper underlining principle, so far unknown. (The larger shift at higher latitudes is probably due to a slight decrease of field values in 2007, which is seen in WSO data. Effects due to temporal evolution are largest at high poles because of their larger temporal separation).

6. Cumulative Flux Density Around the Equator

[27] Figure 6 gives a closer view of the cumulative flux density in the equatorial region during the two minimum time perihelion scans. During the first scan in 1994–1995 the unipolar regions extend quite close to the equator. The region where notable deviations from the linear evolution take place (where significant amounts of both polarity appear) is located roughly from −15° to +18°. In 1994–1995 the main current sheet crossing is located at the latitude of about −1.1°. This is in a fair agreement with the result of Figure 5. In addition to this main HCS crossing, there are smaller peaks (local extrema) in the cumulative flux density around latitudes −15°, −14°, −11°, −7°, +5°, +8°,+16° and +18°. These indicate other current sheet crossings observed by Ulysses when flying at latitudes sufficiently low to see the alternating sectors of the rotating Sun. Note that the largest local minima in cumulative flux density are located approximately in 10° latitude steps at latitudes −11°, −2°, +8° and +18°. Since Ulysses crosses 20° in latitude during one synodic solar rotation, this indicates a dominant, and quite symmetric four-sector structure in the global solar field at this time.

[28] During the third perihelion scan in 2007 the detailed structure of the HMF around the equator is quite different from that in 1994–1995. The equatorial region including notable sheet crossings is now considerably wider, extending at least from −28° to +24°. Also, contrary to the situation in 1994–1995 of one major minimum only, there are now two roughly equally high peaks in the cumulative flux density at latitudes of about −13° and +5°. Between these two maxima the cumulative flux density reaches a minimum at −2° latitude. In addition, several smaller but still quite notable current sheet crossings are seen in 2007, e.g., those at about −8° and −5°. The separation of the two main maxima by roughly 20° with two smaller crossings in between indicates that the HMF consisted of a dominant two-sector structure and a subdominant four-sector structure at that time.

[29] Unfortunately the observed structure of the cumulative flux density around the equator cannot alone give an unambiguous picture of the HCS structure, e.g., on the HCS shift, because of the following reasons. Considering the fast latitudinal motion of Ulysses (20° per solar rotation), the observations are critically dependent on the timing of Ulysses orbit with respect to solar longitude, i.e., the results depend on the longitude phasing of the orbit. In addition to the longitude phase, the HCS tilt angle and the possible shift of the HCS affect the observations in the equatorial region.

[30] We have studied the effect of these three parameters on Ulysses observations at the equator using a simple model of a flat HCS which may be tilted and shifted, varying the tilt angle, the shift angle and the longitude phase. These model assumptions better reflect the situation in 2007 but for 1994–1995 they are overly simplified since, as mentioned above, there was a four-sector structure in 1994–1995 which cannot be modeled by a simple tilted dipole HCS structure. However, even this simple model is suffi-

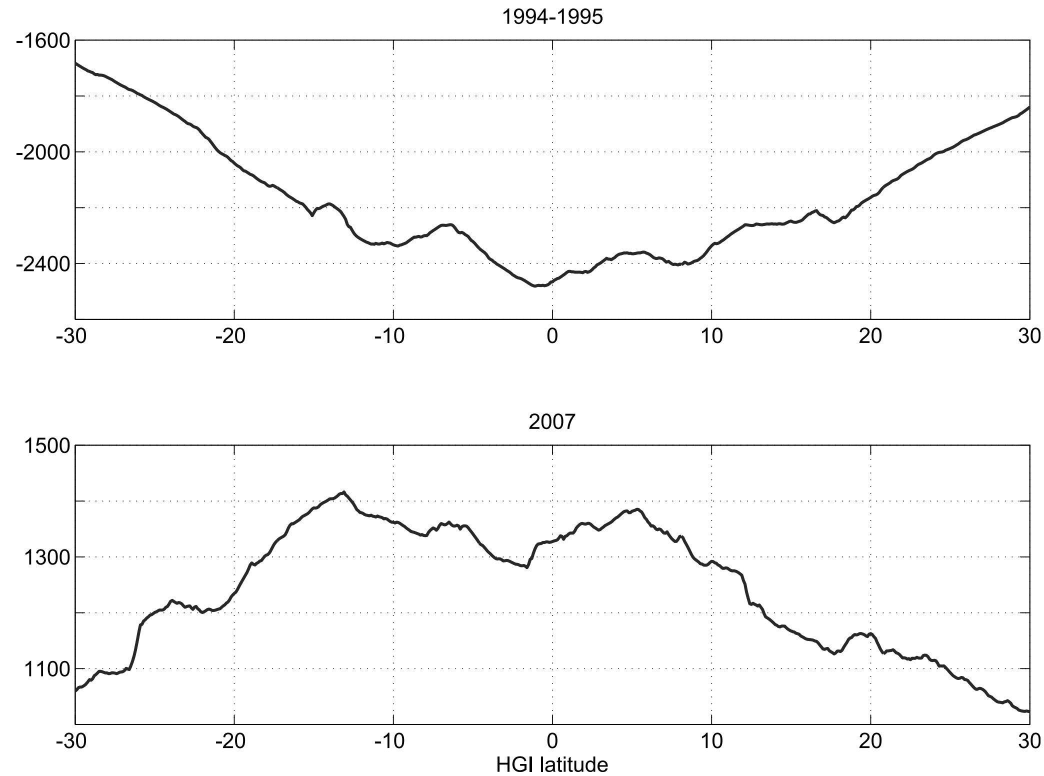

Figure 6. Cumulative flux density around the equatorial region as a function of heliographic latitude during the two minimum time perihelion scans.

ciently versatile to demonstrate the various effects caused by the three parameters.

[31] Figure 7 describes the expected cumulative flux density that would be observed around the equator for different values of the three parameters, leading to different HCS structures. Each panel shows four different flux density patterns, corresponding to varying the HCS shift from 0° (no shift; blue curve), to −5° (green), −10° (red) and −15°

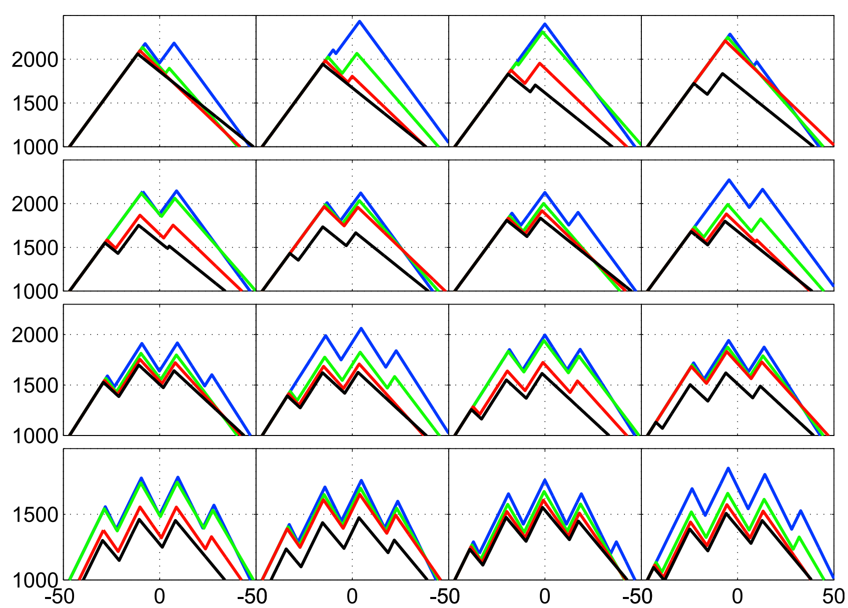

Figure 7. Model results for the cumulative flux density around the equator for a flat, tilted HCS. Each panel shows four flux density patterns when varying HCS shifts from 0° (no shift, blue curve) to −5° (green), −10° (red), and −15° (black). On each row, equatorial longitude phase increases from left to right from 0° to 270° in 90° steps. On each column the HCS tilt angle increases from top to bottom from 10° to 40° in 10° steps.

(black). On each row, the equatorial longitude phase increases from left to right from 0° to 270° in steps of 90°. Here the equatorial longitude phase means the longitude of Ulysses line-of-sight footpoint on solar surface at the time when the probe crosses the heliographic equator. The zero equatorial phase corresponds to the model situation where the HCS is at zero latitude at the equatorial footpoint longitude. Similarly, the 90° equatorial phase corresponds to the situation where the HCS is at the highest latitude at the equatorial footpoint longitude, etc. (Note that no delay was imposed between source and Ulysses in the model.) On each column the HCS tilt angle is increased from top to bottom from 10° to 40° in steps of 10°.

[32] Figure 7 shows clearly that when the tilt angle increases the latitudinal width of the complex equatorial HCS region increases notably. Also, with larger tilt angles, the fluctuation of the cumulative flux density with the (Ulysses synodic) solar rotation period gets stronger and the differences associated with the different longitudinal phase and HCS shift are reduced. For smaller tilt angles the differences due to longitudinal phase and HCS shift become more noticeable. The longitudinal phase is perhaps the most important parameter to determine whether one observes one main peak or two roughly equal peaks around the equator. This is clearly seen, e.g., on the second row where, for zero shift, one observes one dominant peak for 180° phase and two equal maxima for 0° phase. Note, however, that these longitude phase values are not the same for a nonzero shift angle and, e.g., for 10° HCS shift, one observes one dominant peak for 0° and 270° phases and two equal maxima for 90° phase. Figure 7 also shows an interesting fact that, despite the southward HCS shift, the highest peak can still be located above the equator. This is the case, e.g., for −5° shift in the 90° longitude phase situation for all depicted tilt angles.

[33] Concluding, the model results depicted in Figure 7 show that it is not easy, maybe not even possible, to determine the exact value of the possible southward shift of the HCS from the equatorial cumulative flux density alone. This emphasizes the importance of the above approach concentrating on the high-latitude sections of Ulysses orbit. Finally, let us note that models including a four-sector or even a more complicated sector structure would, naturally lead to even more versatile and mixed situation. However, in case of a four-sector structure like in 1994–1995, it is simply more probable to cross HCS in such a way to produce one clear extremum close to the equator, than in case when the HCS is dominated by a two-sector structure like in 2007 when the temporal separation of such maxima is larger. This partly explains the different structures observed at these times.

7. Comparing Ulysses Data With WSO Maps

[34] We have also compared Ulysses observations with the simultaneous predictions of HMF structure given by the synoptic maps of the Wilcox Solar Observatory computed with the radial PFSS model. Note that one synoptic map includes observations from different longitudes at different times.

[35] Thus, the agreement between Ulysses and WSO may suffer if Ulysses and Earth are located at widely different heliographic longitudes. This is the case in 1994–1995 when Ulysses and Earth are separated by almost 180° in longitude during Ulysses equatorial crossing. On the other hand, Ulysses and Earth have almost the same longitudes during equatorial crossing in 2007. Note also the rather coarse latitude resolution of WSO synoptic maps which, even at its best at the equator, is only 3.8°. This is considerably coarser than the 0.1° binning of Ulysses data.

[36] Figure 8 presents the WSO radial PFSS synoptic maps and the backtraced Ulysses HMF footpoints in solar corona during three Carrington rotations around the equatorial crossings in 1995 and 2007. When finding the coronal source longitude of the HMF measured by Ulysses we used the measured solar wind speed and the theoretical solar wind speed profile [*Cranmer*, 2004]. The HMF footpoint in Figure 8 varies in a zigzag manner because of changes in solar wind speed especially at current sheet crossings.

[37] Figure 8 verifies that the HMF indeed had a fairly symmetric four-sector structure around the equator in 1994–1995, in agreement with the discussion of Figure 6. Similarly, there was a clearly asymmetric four-sector structure (or a dominant two sector structure with a subdominant four-sector structure) in 2007, as noted earlier.

[38] In 1995, during Carrington rotation (CR) 1892 the northern field is observed in WSO maps along the Ulysses footpoint between −16° and −13° of latitude, 135° and 60° of longitude. This is in good agreement with Figure 6 where change in slopes shows that Ulysses observed a region of northern polarity between latitudes −15° and −14°. During CR 1893 the northern polarity in WSO map is first observed between latitudes −8° and −5°, while Ulysses observed it between −10° and −6°. The final current sheet crossing in WSO is seen at latitude 0°, while the cumulative flux density reached the minimum value at −2°. This demonstrates a good overall agreement between Ulysses and WSO maps for this part of the orbit. However, according to Figure 6 there should be a region of southern polarity between 5° and 8° but this is not seen in the WSO map. Also, the last region of southern polarity observed by Ulysses between 16° and 18° is not clearly seen in WSO, although the footpoint is quite close to southern fields during CR 1894 at the same latitude at longitude 205°.

[39] Thus, we find out that Ulysses cumulative flux density and WSO maps are in a good agreement in the Southern Hemisphere, but in the northern side the WSO maps cannot well predict all the current sheet crossings observed by Ulysses. The main reason for this difference is most likely the "vantage point effect" of the WSO model, i.e., that when observing the photosphere from the ecliptic plane, the ±7.25° difference between the HGI plane and the ecliptic plane leads to an annually varying preference of fields predicted by WSO [see, e.g., *Wang and Sheeley*, 1992]. Accordingly, the WSO predicted HCS location is shifted southward during Spring and northward during Fall. Since the equatorial crossing in 1995 occurred in Spring the vantage point effect shifts the predicted HCS southward, reducing the extent of southerly fields to the north.

[40] In 2007 the first current sheet crossings in the cumulative flux density were found at latitudes of −28° and −24°, but in WSO map the current sheet remains somewhat above the HMF footpoint at this time. The polarity turn at the highest value of the cumulative flux density at latitude −13° is observed at a somewhat higher latitude of about −8° in the WSO map. The following small peak at Ulysses

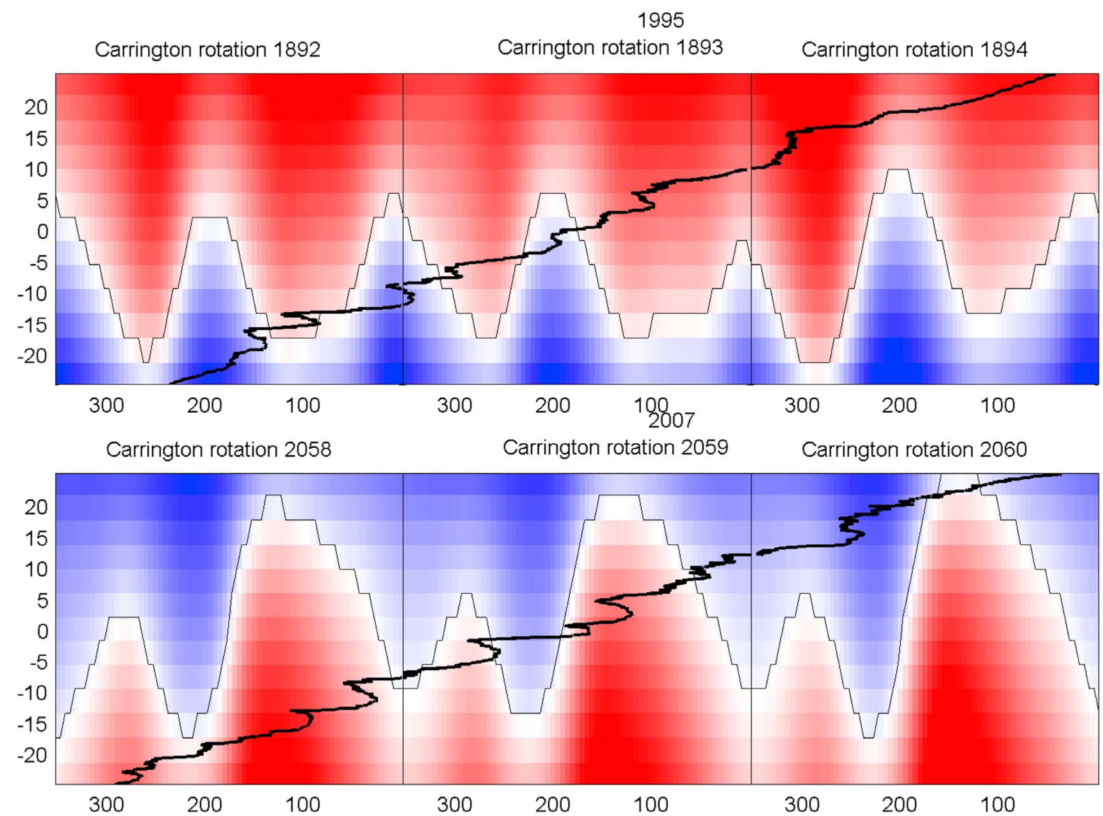

Figure 8. WSO synoptic maps around the equator during the fast scans in 1995 and 2007. Thick black curve presents the coronal foot point location of the solar wind observed by Ulysses. Thin solid line marks the WSO HCS location.

between −8° and −5° is seen as a somewhat larger region in WSO map. The following current sheet crossing at Ulysses from northern to southern polarity at −2° latitude is clearly seen in WSO map. The second high peak in Ulysses cumulative flux density at latitude +5° is seen in WSO map at a slightly higher latitude of about 8°. The last region of southern polarity observed by Ulysses between latitudes 18° and 20° corresponds very well to the WSO current sheet crossing at latitude 21°–23° during rotation 2060. Overall, the agreement between Ulysses and WSO in 2007 is better in the north than in the south. This is again due to the vantage point effect since, in Fall 2007 the Earth was located above the solar equator above latitude 6°. This led to a corresponding northward shift of the WSO predicted HCS location.

8. Conclusions

[41] We have studied the hemispheric asymmetry of the high-latitude unipolar fields and the heliospheric current sheet using Ulysses magnetic field measurements during the three fast latitude scans (perihelion passes) in 1994–1995, 2001–2002, and 2007. We have calculated the cumulative flux density (scaled by r^2 to 1 AU) using radial magnetic field values averaged to 0.1° latitude bins, which guarantees uniform sampling in latitude.

[42] We have found that the magnitude of the radial field in the unipolar regions of the Southern Hemisphere is larger than in the Northern Hemisphere during both minimum time scans in 1994–1995 and 2007. The hemispheric difference in the radial field is found to be roughly the same, about 0.2 nT, during both scans. Using the total flux conservation, we find that the northern field area is some 5%–10% larger than the southern area in 1994–1995, and some 5%–15% larger in 2007. This result for 1994–1995 is in a good agreement with several earlier observations using different types of Ulysses data [*Simpson et al.*, 1996; *Forsyth et al.*, 1996; *Crooker et al.*, 1997] or HMF observations at 1 AU [*Mursula and Hiltula*, 2003].

[43] Our new result of a smaller flux density and larger area in the north again in 2007 shows that the high-latitude unipolar regions in solar cycle 23 were similarly asymmetric in the same direction and by roughly the same amount as in several earlier cycles [*Mursula and Hiltula*, 2003; *Hiltula and Mursula*, 2006], although SC 23 is rather exceptional at least among the recent cycles. (Accordingly, the solar ballerina was still bashful in SC 23). In particular, the polar fields are unusually weak in SC 23 [*Smith and Balogh*, 2008], and the polar coronal holes smaller than, e.g., in SC 22 [*Harvey and Recely*, 2002; *Kirk et al.*, 2009]. As a result, the tilt angle in SC 23 is exceptionally large compared to the respective phase of earlier cycles. This was also verified by the present Ulysses observations of a considerably wider (by about ±10°) HCS region around the equator in 2007 compared to 1994–1995. The presently found significant asymmetry in 2007 also clarifies the recent result of a very small hemispheric asymmetry when using ecliptic observations [*Mursula and Virtanen*, 2010].

[44] The larger area in the north is equivalent to a southward shift of the HCS, which was found to be roughly about −2° both in 1994–1995 and in 2007. Note that these values are longitudinally averaged shifts. The result for 1994–1995 is in a very good agreement with earlier estimates based on WSO and OMNI data [*Mursula and Hiltula*, 2003; *Zhao et al.*, 2005]. We also discussed the dependence of the field asymmetry and HCS shift on the equatorial limit of the fitting range (extent of unipolar regions), and found that in both passes the results are insensitive to the exact value of this range.

[45] We studied the detailed structure of the equatorial region of HCS crossings, comparing Ulysses observations with simultaneous HMF predictions given by the WSO synoptic maps computed with the radial PFSS model. The two observations agree, e.g., on the dominantly four-sector structure in 1994–1995 and the dominantly two-sector structure (with subdominant four-sector structure) in 2007. The detailed comparison of HCS crossings depicted better agreement below the heliographic equator in 1994–1995 and above the heliographic equator in 2007, suggesting that remaining disagreement is mainly affected by the varying vantage point of WSO observations.

[46] We noted that HMF observations around the heliographic equator cannot alone give unambiguous information of the possible HCS shift because the fast latitudinal motion of Ulysses (20° per solar rotation) makes the observations critically dependent on the timing of Ulysses orbit with respect to solar longitude.

[47] We demonstrated this using a simple model of a flat HCS which may be tilted and shifted, varying the tilt angle, the shift angle and the longitude phase. We found that with large tilt angles, typically 30° or more, the difference due to HCS shift is reduced. For small tilt angles the value of the possible HCS shift is greatly dependent on the longitudinal phase. Even if the HCS is shifted southward, the highest peak of the observed cumulative flux density may still be located above the equator, leading to an erroneous conclusion. This shows that it is not easy, maybe not even possible, to determine the possible HCS shift from the equatorial HMF observations alone, thus emphasizing the importance of studying the high-latitude sections of Ulysses orbit.

[48] As noted in the Introduction, during the review process of this paper a revised paper by *Erdös and Balogh* [2010] was published, which corrects the results of *Erdös and Balogh* [1998] and further verifies the southward shift for the first fast latitude scan. They also find a roughly similar southward asymmetry for the third fast latitude scan as here, although with a different method using both high-latitude and equatorial observations. However, their analysis did not consider how the result would depend on the parameters, e.g., the solar longitude, affecting the observations at the equator.

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