

RECENT OBSERVATIONS OF THE HELIOSPHERIC MAGNETIC FIELD AT ULYSSES: RETURN TO LOW LATITUDE

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ABSTRACT

Ulysses recently completed a second slow latitude scan of the northern heliosphere, a descent from 80.2°N in July 1995 to the solar equator in December 1997. These recent magnetic field observations complement those from the south hemisphere and reveal new features as well as the effect of the changing solar cycle. Five topics are emphasized in this report. (1) The solar wind latitude structure is affected by the low inclination of the heliospheric current sheet (HCS) which prevents fast high latitude wind from reaching down into the ecliptic and leads to three distinct zones, the middle or transition zone consisting of large periodic Corotating Interaction Regions (CIRs). The HCS is first observed in the middle zone at unexpectedly high latitudes. (2) In the Corotating Rarefaction Regions (CRRs) separating the CIRs, a large discrepancy is found between the observed and Parker spiral angles with the field being underwound by $\approx 30^\circ$. (3) Fluctuations in the field are again predominantly Alfvén waves in the fast wind so that the variances undergo periodic variations in level in the transition zone. (4) The magnetic flux parameter, $r^2 B_R$, differs in the three zones being constant at high latitudes, enhanced in mid- and depleted at low- latitudes. The observations are consistent with displacement of magnetic flux from low to mid-latitudes. (5) An asymmetry between the radial components in the south and north hemispheres is evident in observations being made in the ecliptic by WIND. The observations agree with a southward displacement of the HCS as inferred from the Ulysses cosmic ray measurements. A time variation during the fast latitude scan from the south to the north pole obscured this asymmetry in the Ulysses magnetic field measurements.

INTRODUCTION

In April, 1998, Ulysses returned to aphelion at 5.3 AU, slightly below the ecliptic plane, completing the first full orbit since leaving Jupiter in February 1992. In the interim, the spacecraft reached 80.2° S at 2.2 AU in Sept. 1994, executed a "Fast Latitude Scan" of about 6 months crossing the equator to 80.2° N (in July 1995) and the recent slow descent from the north polar region to the equator. A series of publications have documented highlights of the mission including the first observations at high latitude (*Science*, 268, 1005-1036, 1995) and the results of the pole-to-pole transit (*Geophys. Res. Lett.*, 22, 3297-3432, 1995; *Astron. Astrophys.*, 316, 279-536, 1996). The recent return to the equator has provided a second "Slow Latitude Scan".

A noteworthy event occurred with the reappearance of the slow solar wind in August 1996 at a latitude of 28°N. Preliminary reports of the solar wind and magnetic field observations have already appeared (Gosling *et al.*, 1997; Forsyth *et al.*, 1997). This article presents recent field observations with emphasis on the transition from the fast high latitude wind to the slow low latitude wind with a discussion of specific results proceeding from a review of the first full orbit and the multiple latitude scans.

Fortunately, measurements have been continuously available from in-ecliptic spacecraft, IMP-8 and WIND. These measurements are essential in distinguishing spatial from temporal variations. Details of the magnetic field investigations are described in Balogh *et al.* (1992) and Lepping *et al.* (1995).

OBSERVATIONS

Solar Wind Structure. An overview of the solar wind and magnetic field observations as Ulysses descended from the pole to the ecliptic is shown in Figure 1. Plotted from top to bottom are the solar wind speed (V), field magnitude (B) and the observed (Φ_B) and Parker (Φ_P) spiral angle (Parker, 1963), the latter computed from V and the sidereal equatorial solar rotation rate ($360^\circ/25.4$ days). The parameters are shown as a function of time from mid-1995 to mid-1998 with heliographic latitude indicated along the upper scale. WIND velocities, obtained from the MIT web site, are also shown.

The solar wind speed exhibits three distinct regions or latitude zones. From 80° to 28° , fast wind originating from the north polar coronal hole is present. From 28° to 10° , fast wind from high latitudes alternating with slow wind from lower latitudes form a series of Corotating Interaction Regions or CIRs (one CME is also present). Below 10° , only slow wind is present.

The three zones are consistent with a model in which the inclination of the Heliospheric Current Sheet/HCS (or the tilt of the axis of the equivalent solar magnetic dipole) is low being approximately 5° . The solar wind increases from low (350 km/sec) to high (700 km/sec) speeds between about 10° and 23° with fast wind above 23° (heliomagnetic latitudes). Thus, the changing inclination of the magnetic coordinates causes the lower edge of the fast wind to vary between 28° and 18° and the upper edge of the equatorial slow wind to reach 15° (heliographic latitudes). Because of the low inclination and the angular widths of the zones of the slow and transition speed winds, the fast high latitude wind is not able to reach down into the ecliptic.

The figure shows that crossings of the HCS into the negative (south) magnetic sector began shortly after Ulysses reached 28° . The presence of the current sheet at such high latitudes appears inconsistent with the low inclination of the HCS of only 5° inferred from solar wind structure. Furthermore, the HCS is usually found to be embedded in slow solar wind, not near the lower boundary of the fast wind. Possible explanations are a local bump or excursion of the HCS associated with the magnetic fields of an active region that was present at this time for many solar rotations (e.g., Figure 4 of Forsyth *et al.*, 1997) and/or distortion of the current sheet with increasing heliocentric distance caused by the wind shear as demonstrated in the Pizzo model (Pizzo, 1994). The solar wind flows, magnetic sector structure and current sheet excursions may possibly be related to the solar magnetic field and coronal holes by means of the expansion factor – solar wind relation developed by Wang and Sheeley (1993).

Rarefaction Regions. One of the distinctive features of Figure 1 is the presence of very low values of B that appear at quasi-periodic intervals. Figure 2 shows an example of V and B at higher time resolution (hourly averages) so that this feature is more readily evident. The regions of low B (and correspondingly low solar wind densities, N) occur within regions of monotonically decreasing V . The combined figures show that this correlation occurs in association with CIRs and is especially evident in the mid-latitude zone where large CIRs are present. The same correlation is also evident in earlier Ulysses observations in 1993 between 10° and 30° S.

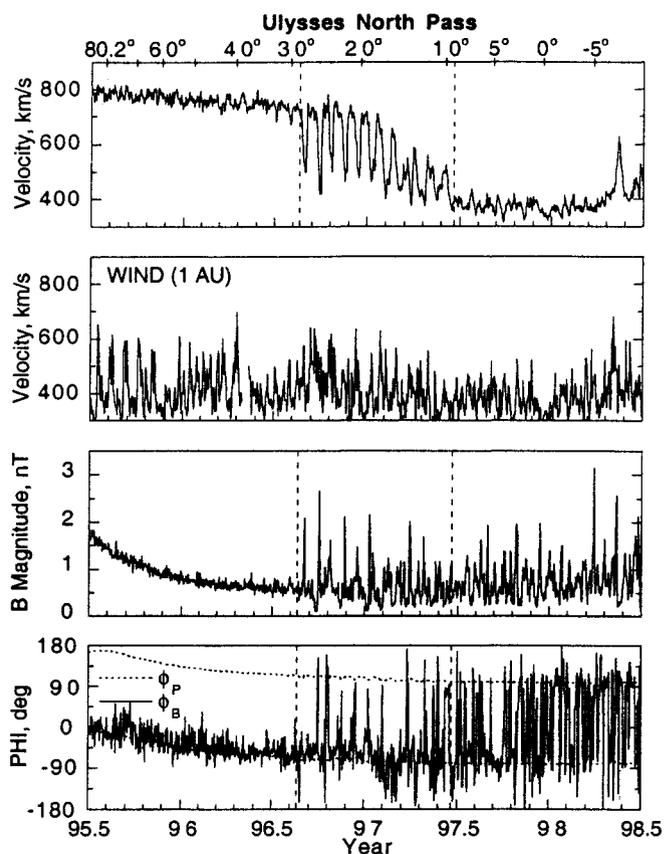


Fig. 1. Overview of solar wind speed, magnetic field magnitude and spiral angle during the slow descent from the north polar region. Daily averages over an interval of three years are plotted. The vertical dashed lines identify the three latitude zones discussed in the text. The dashed curves in the bottom panel show the Parker spiral angle for the two magnetic sectors derived, in part, from the measured wind speeds at Ulysses. WIND velocities are also shown to distinguish spatial from temporal variations.

These Corotating Rarefaction Regions/CRRs were first noted in Pioneer 10, 11 data and attributed to continuous expansion of fast solar wind in a region of decreasing speed so that faster wind simply outruns the trailing slower wind (Smith and Wolfe, 1977). CRRs have the curious property that when the velocities are used to extrapolate back to the sun the entire wind appears to originate at the same longitude (Nolte and Roelof, 1973). For this reason, energetic particle investigators have referred to them as "dwells".

An aspect of CRRs that has been ignored until recently is the relation between the observed and Parker field spirals within these regions. Figure 2 shows a systematic difference between ϕ_B and ϕ_P in the rarefaction region such that the field is underwound (more radial). A histogram of the differences in the two angles (Figure 3) covering latitudes between 30° and 10° shows that this conclusion holds generally. The Most Probable Value of the difference is surprisingly large, $\approx 25^\circ$, and not attributable to measurement uncertainties. Comparable histograms at high latitudes, conversely, consistently exhibit Most Probable Values of 0° . (The average values are characteristically different from zero as a consequence of ever-present asymmetries in the distribution functions.) This result was noted in earlier Ulysses measurements near 5 AU at southern latitudes and was also confirmed as being present in even earlier Pioneer 10, 11 magnetic field data obtained within CRRs (Murphy and Smith, 1996).

How is such a large discrepancy in the spiral angle to be explained? An obvious possibility is that the end of the field line attached to the sun is rotating at a different angular velocity than assumed. The equation for the Parker spiral (Parker, 1963) indicates how much of a reduction in Ω would be required. At 5 AU, a shift of 30° in ϕ_B would imply a large reduction by a factor of 5 or an increase in the rotation period to a value > 100 days. Clearly, such a persistent rotation period is not plausible. However, the foot of the field line at the sun could rotate much more slowly over a limited time/longitude interval.

Could the Alfvén waves characteristically found inside the CRRs be a contributor? One way to assess their possible influence is to consider the magnitude of the fluctuating electric fields that accompany the waves as compared with the change in E field that would be needed to account for the observed spiral angle. The wave field is given by $\Delta E = C_A \cdot \Delta B$, i.e., the wave speed times the variation in the magnetic field. The electric field in inertial space associated

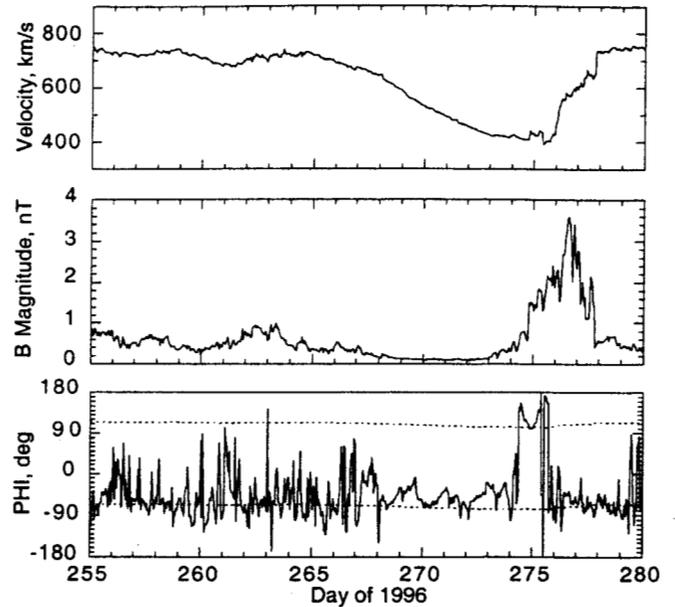


Fig. 2. Example of speed, field strength and spiral angle variations associated with a Corotating Rarefaction Region. Hourly averages are shown. The monotonic decrease in speed between days 267-275 is accompanied by very low field magnitude resulting from the expansion. The bottom panel shows the characteristic deviation of the observed (solid) from the Parker spiral angle (dashed) discussed in the text.

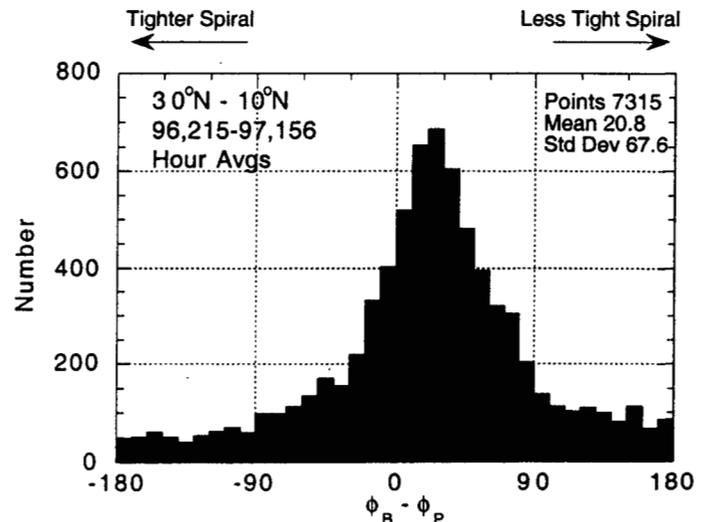


Fig. 3. Histogram of the differences between the observed and Parker spiral angles in the mid-latitude zone ($10^\circ - 30^\circ$) containing CIRs and CRRs. Both the mean and the most probable values show a substantial departure in the sense of the field direction being more radial than the model predicts. The solar wind speed was used to compute the expected angle.

with the Parker spiral is $E = V_R B \phi$. Assuming $\Delta B \approx B$, $\Delta E/E = C_A/V_R \leq 0.1$. However, the change in E associated with a 30° change in spiral angle is $\approx \cos(30^\circ)$ or about 0.15. Thus, the wave field is too small, even assuming that the entire field, rather than only a fraction of the field associated with an asymmetry of some kind, is responsible to explain the departure.

A property of CRRs is the very low field magnitude, B , and solar wind density, which are reduced by about an order of magnitude compared to the average values that would be expected at 5 AU based on the Parker model. Such a decrease is consistent with a time variation or non-radial expansion of the CRR that is not included in the model. Careful analysis of this possibility is needed.

Variations and covariances. Prior Ulysses studies have used variances and covariances in the field components to identify Alfvén waves, to establish their basic properties and to demonstrate that they are a characteristic feature of the fast high latitude wind (Smith *et al.*, 1995a). A parameter that has proven useful is $\sigma^2_S = (\sigma^2_R + \sigma^2_T + \sigma^2_N)/B^2$, i.e., the power in the fluctuations represented by the sum of the variances in the components referred to the square of the average field strength. Figure 4 is a plot of this parameter based on hourly values obtained during the descent from 80° to the equator.

Is the presence of the three solar wind latitude zones evident in the variances? From 80° to 30° , σ^2_S decreases monotonically from ≈ 0.4 to 0.25. Between 30° and 18° , σ^2_S varies periodically between 0.2 and values near zero. Below 18° , both the average level and the variations in σ^2_S are substantially lower. Vertical lines have been added to make these distinguishing characteristics more obvious.

At high latitudes, the sum of the (unnormalized) variances follows a power law which provides a least squares fit to the data of $r^{-3.1}$. This dependence is similar to that found in the southern hemisphere (Forsyth *et al.*, 1996). They are both consistent with the waves being generated near the sun and decreasing with distance as predicted by the WKB approximation.

That the variances are associated with Alfvén waves is shown by the covariances or cross-correlations between the variations in the field and solar wind velocity components (Figure 5). The cross correlations are large, ≈ 0.85 , at 80° and decrease monotonically to ≈ 0.50 at 30° . Below that latitude, the average values decrease rapidly to an average of zero. Thus, the fluctuations at the highest latitudes are almost pure Alfvén waves.

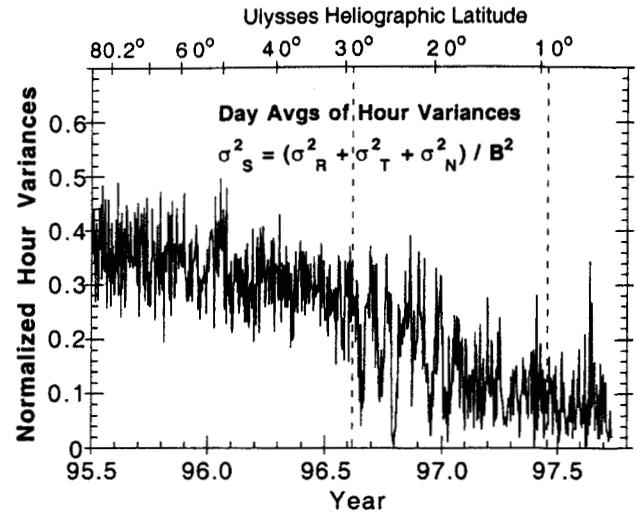


Fig. 4. Variances in the field components during the descent in latitude. Daily averages of the sum of the variances in the components normalized by the corresponding values of field magnitude squared are shown. The dashed vertical lines again identify the three distinct latitude zones.

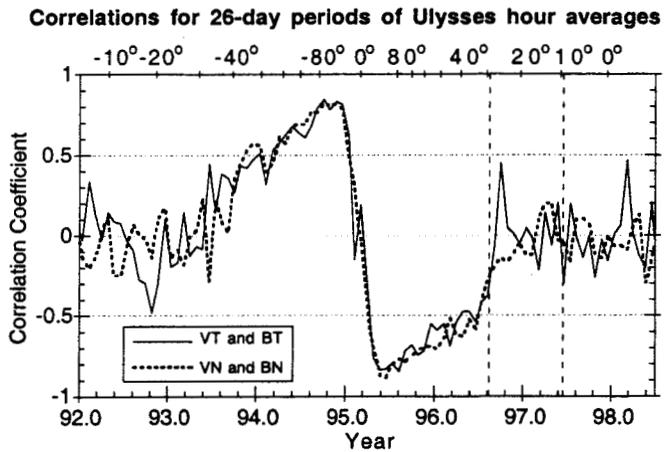


Fig. 5. Correlation coefficients representing Alfvén waves over the full range of latitudes. The Alfvén wave relation implies that the magnetic and velocity variations are correlated. The cross-correlation coefficients for the transverse field and velocity components are shown over a six year period during which Ulysses descended to the south pole, returned to the equator, ascended to the north pole and returned again to the equator. The coefficients are large and increasing above $\approx 45^\circ$ reaching peak values at the highest latitudes. The signs change at 0° because the average field direction reverses from inward to outward while the waves propagate outward in both hemispheres. The vertical dashed lines identify the same three regions as in foregoing figures.

The periodic changes in σ^2_S between 30° and 18° are closely correlated with the periodic variations in V and B apparent in Figure 1. The abrupt drops in σ^2_S coincide with the minima in V while the large values coincide with the presence of fast solar wind. This correlation and the disappearance of large values below 18° is consistent with the waves being restricted to the high speed, high latitude wind and being absent or much weaker in both the slow wind and the transition region between fast and slow winds.

Radial Field Component. The radial component is basically the independent variable which determines the azimuthal field component (given the other terms in the equation for the Parker spiral). It is customarily presumed to represent the HMF at the solar source (the field is constrained to be radial in the source surface models). Studies of B_R have provided information on (1) the absence of a significant latitude gradient, (2) the extent of non-radial flow near the sun and (3) the strength of the polar cap magnetic field (Smith and Balogh, 1995). Baseline in-ecliptic measurements of B_R have been used to distinguish spatial from temporal variations.

The parameter of interest is $r^2 B_R$ which can be regarded as a measure of magnetic flux, an adjustment for the expected radial gradient or an extrapolation of the field component back to 1 AU. Figure 6 shows this parameter at Ulysses, averaged over successive solar rotations, as a function of time and latitude. The vertical bars at each data point are standard errors but are more indicative of time variations than statistical errors or noise in the measurements. This format allows a direct comparison with Figure 1 and shows how $r^2 B_R$ varies within the three solar wind latitude zones.

Ignoring possible time variations temporarily, the radial component appears to be different in the three zones. Above 30° N, the field is essentially constant at about 3 nT(AU)^2 . Between 30° and 10° , the averages are systematically higher having an average value over this range of 3.3 nT(AU)^2 . Below 10° , the field is much more variable (a characteristic feature of the slow wind) and a meaningful average is difficult to discern. The constancy of the field at high latitudes is characteristic of the structure-less fast wind and with the absence of a significant latitude gradient. The increase at mid-latitudes is apparently associated with the periodic excursions of fast and slower wind into these latitudes leading to the large CIRs as indicated by the dashed vertical lines.

It is not obvious that the increased fields inside CIRs would not be compensated by lower than average fields inside the CRRs and that a time variation might not be responsible for the mid-latitude increase. Figure 7 contains both Ulysses and WIND solar rotation averages as a function of the latitude of Ulysses. Standard errors are not shown but are typically less than 0.1 nT at WIND. Data from the portion of the Fast Latitude Scan in the North hemisphere are included to provide a more complete representation as a function of latitude.

The combined data set reveals several important points. First, the mid-latitude increase at Ulysses is not a time variation. Although the data excursions at WIND are larger than at Ulysses, no systematic increase occurred that is coincident with the increase at Ulysses. Furthermore, the earlier Fast Scan data are also consistent with an increase at mid-latitudes that was also not accompanied by a corresponding increase at WIND. Second, in both panels, $r^2 B_R$ is systematically larger at Ulysses. Finally, the values of the equatorial field at WIND and the polar cap fields at Ulysses are sufficiently close as to rule out a significant latitude gradient from equator to pole. Thus, the mid-latitude increase is unique and $r^2 B_R$ is larger there than at the equator or at the pole.

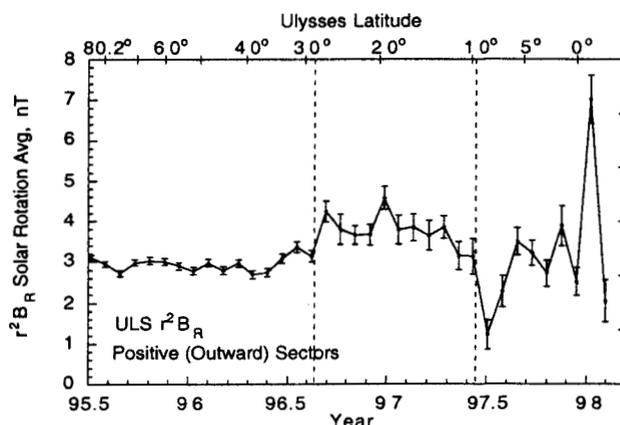


Fig. 6. The magnetic flux as a function of latitude during the recent latitude scan. The product, $r^2 B_R$, which is equivalent to magnetic flux in webers, is shown versus latitude from the north pole to the equator with vertical dashed lines identifying three regions or latitude zones. The vertical "error" bars are standard errors and indicate the field variability during each solar rotation. At high latitudes, only positive (outward) sectors are observed. Below 30° , only values of B_R in positive sectors were used. The flux is independent of latitude from 80° to 30° , is enhanced from 30° to 10° and highly variable in the slow wind below 10° . The striking feature is the increase at mid-latitudes.

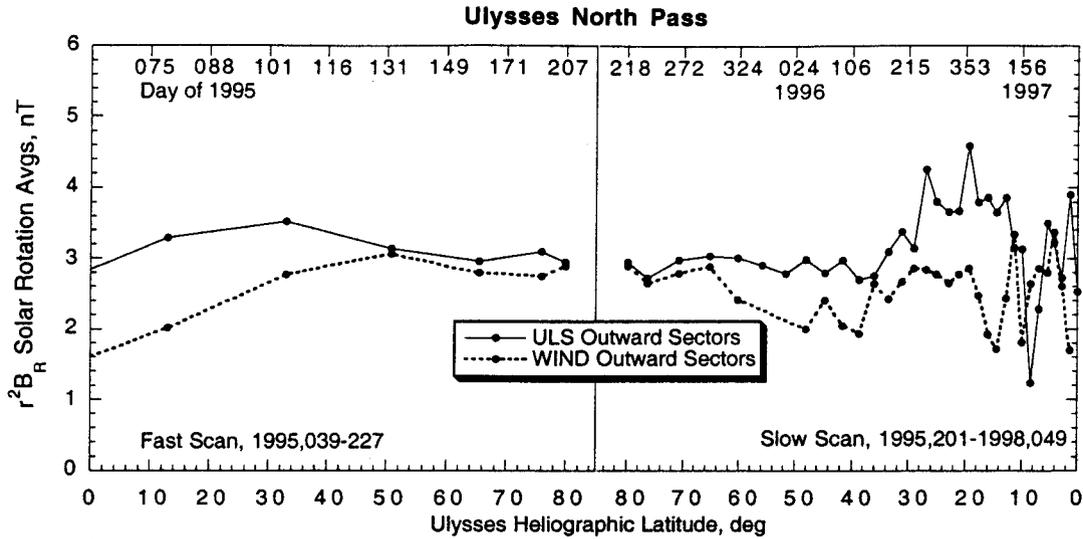


Fig. 7. Magnetic flux at Ulysses in the north hemisphere and in the ecliptic at WIND. The right-hand panel repeats the Ulysses data in figure 6 but plotted as a function of latitude. The WIND data are shown for the solar rotations corresponding to those at Ulysses and are plotted at the Ulysses latitude. The systematically lower values of B_R at WIND and the additional evidence of a mid-latitude increase at Ulysses in the ascent to 80° are evident.

The question immediately arises, is the mid-latitude increase a feature of the field near the sun, representing some aspect of the solar source, or a characteristic feature of solar wind propagation in the heliosphere? Several lines of evidence favor the latter hypothesis. The close correspondence in latitude between the increased fields and the fast-slow stream interaction region has already been noted. In retrospect, previous latitude scans can be shown to involve significant increases of $r^2 B_R$ in the vicinity of mid-latitude CIRs.

Another consideration is that the difference between the low- and mid-latitude field values can be easily accommodated by assuming that B_R falls off slightly less rapidly than r^{-2} . The average value of the radial field at WIND, B_{R0} , is 2.5 ± 0.08 nT, whereas, at mid-latitude, $r^2 B_R = 3.3$ nT(AU)². If B_R actually decreases like r^{-n} , $r^2(r^{-n} B_{R0})$ implies that $n=1.8$. Thus, the field at 1 AU, assumed to be the same at mid-latitude as at the equator, can easily be made compatible with the increase at Ulysses.

The absence of a gradient in B_R at high latitude and an increase at mid-latitude has been proposed in the past in connection with Pioneer 10,11 observations of the so-called "flux deficit" (a departure of the observed field strength from the Parker model) (Winterhalter *et al.*, 1990). Two distinct physical causes have been proposed that would lead to a displacement of magnetic flux from the equator toward higher latitudes. One is the effect of increased magnetic pressure at the equator associated with the stronger spiraling of the Parker field (Suess *et al.*, 1985). The other is the increased plasma and field pressure in the equator associated with the compression of the solar wind inside CIRs (Pizzo and Goldstein, 1987). The combined Ulysses-WIND observations of a weaker field in the equatorial region than over the poles is qualitatively consistent with such a displacement of flux to mid-latitudes.

This hypothesis can be quantified by considering conservation of magnetic flux over the northern hemisphere. The total flux, Φ_T , can be estimated, as in the past, by assuming that near the sun the magnetic pressure associated with the initial dipole configuration relaxes to an equilibrium state such that B_R is independent of latitude. Then, $\Phi_T = 2\pi r^2 B_{RP} = 6\pi r^2$, where $B_{RP} = 3.0$ nT is the radial field at high latitudes at Ulysses. The flux at latitudes below 30° is $\Phi_0 = \Phi_T (1 - \cos(30)) = 0.5 \Phi_T$ and the flux at mid-latitudes is $\Phi_M = 2\pi r^2 (3.3) (\cos(30) - \cos(10))$. The remaining calculation is the reduced flux at low latitude, $\Phi_L = 2\pi r^2 (\cos(10)) B_{RL}$ which must equal $\Phi_0 - \Phi_M$ or the low latitude radial component, $B_{RL} = 2.5$ nT as observed at WIND. Thus, conservation of magnetic flux is consistent with the mid-latitude increase and with the flux deficit in the equatorial region.

North-South Asymmetry

Measurements of both galactic and anomalous cosmic rays during the Ulysses fast latitude scan (FLS) exhibit a significant difference in particle fluxes in the north and south hemispheres (Simpson *et al.*, 1996; Heber *et al.*, 1996). The latitude gradients are essentially the same but the intensities are greater in the north hemisphere. Alternatively, the data in the north and south can be made to coincide by assuming the plane of symmetry of the heliosphere was not at the heliographic equator but was displaced southward by about 10° . Support for an asymmetry was provided by the solar wind speed measurements which were systematically higher in the north and which could also be symmetrized by a displacement of 10° S. Further supporting evidence was elicited from contours of the neutral line on the solar magnetic source surface which showed a southward displacement of about the same amount (Heber *et al.*, 1996).

These observations motivated searches in the Ulysses magnetic field measurements for a possible north-south asymmetry. The earliest attempt, admittedly only qualitative, was inspection of the HCS contour based on the seven current sheet crossings observed as Ulysses traveled from south to north during the FLS (Smith *et al.*, 1995b). A more careful quantitative analysis was carried out which compared the magnetic fluxes in the two hemispheres and identified the time/latitude at which they were equal (Erdős and Balogh, 1998). Neither approach produced evidence of an asymmetry of the magnitude required by the energetic particle observations.

A clear understanding of what such an "offset" of the HCS would actually consist of and how the magnetic field in the two hemispheres would be affected is essential. The current sheet would not simply be displaced southward along the sun's magnetic axis because that would lead to non-radial fields (and solar wind flows) above and below the current sheet. A physically plausible asymmetry shown in Figure 8 involves a "conical" current sheet that is displaced southward at all latitudes and resembles the proverbial "ballerina skirt". The magnetic fluxes in the two hemispheres occupy different solid angles so that, assuming they are equal as required by the divergence-free field condition, the radial components are different. As indicated, B_R would be greater in the south hemisphere.

Curiously, isolated reports of a N/S asymmetry in the magnetic field have appeared from time to time but have not attracted much attention (Wilcox, 1972). The field has occasionally been observed to have a single polarity as measured by in-ecliptic spacecraft or Earth-based solar magnetographs near solar minimum when the HCS inclination is also minimal and the observer might be considered to be near the solar equator but continuously above the current sheet. The field has also occasionally revealed a correlation with heliographic latitude indicative of a N/S asymmetry with, for example, stronger fields in one hemisphere (Luhmann *et al.*, 1988).

Could an asymmetry go unobserved in the Ulysses data although actually present? A limitation of the Ulysses orbit is that the spacecraft spends time first in one hemisphere measuring inward-directed fields exclusively and then time in the other hemisphere measuring outward-directed fields exclusively. When consistently above the current sheet in the south and then in the north hemisphere, Ulysses did not sample fields in both sectors during a single solar rotation. Evidence of an asymmetry requires that the field configuration and strength remain essentially unchanged during the 5 month interval of the "fast" scan.

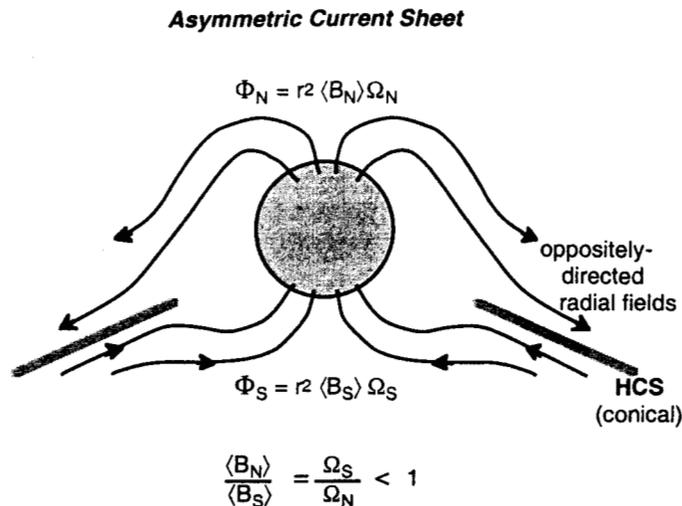


Fig. 8. Schematic of an asymmetric heliospheric current sheet. Conditions near the sun are shown in two dimensions for simplicity. The grey circle represents the photosphere. The source surface (not shown) lies at the inner edge of the HCS. The solar wind and field lines (shown with arrow-heads) must be radial so the current sheet (solid heavy lines) is conical (not simply displaced southward such as might be inferred). The symmetry axis is aligned with the equivalent magnetic poles but will generally be tilted relative to the sun's rotation axis. Because equal total signed magnetic flux is confined to different solid angles, the average value of B_R is smaller above the current sheet than below it (for the configuration shown).

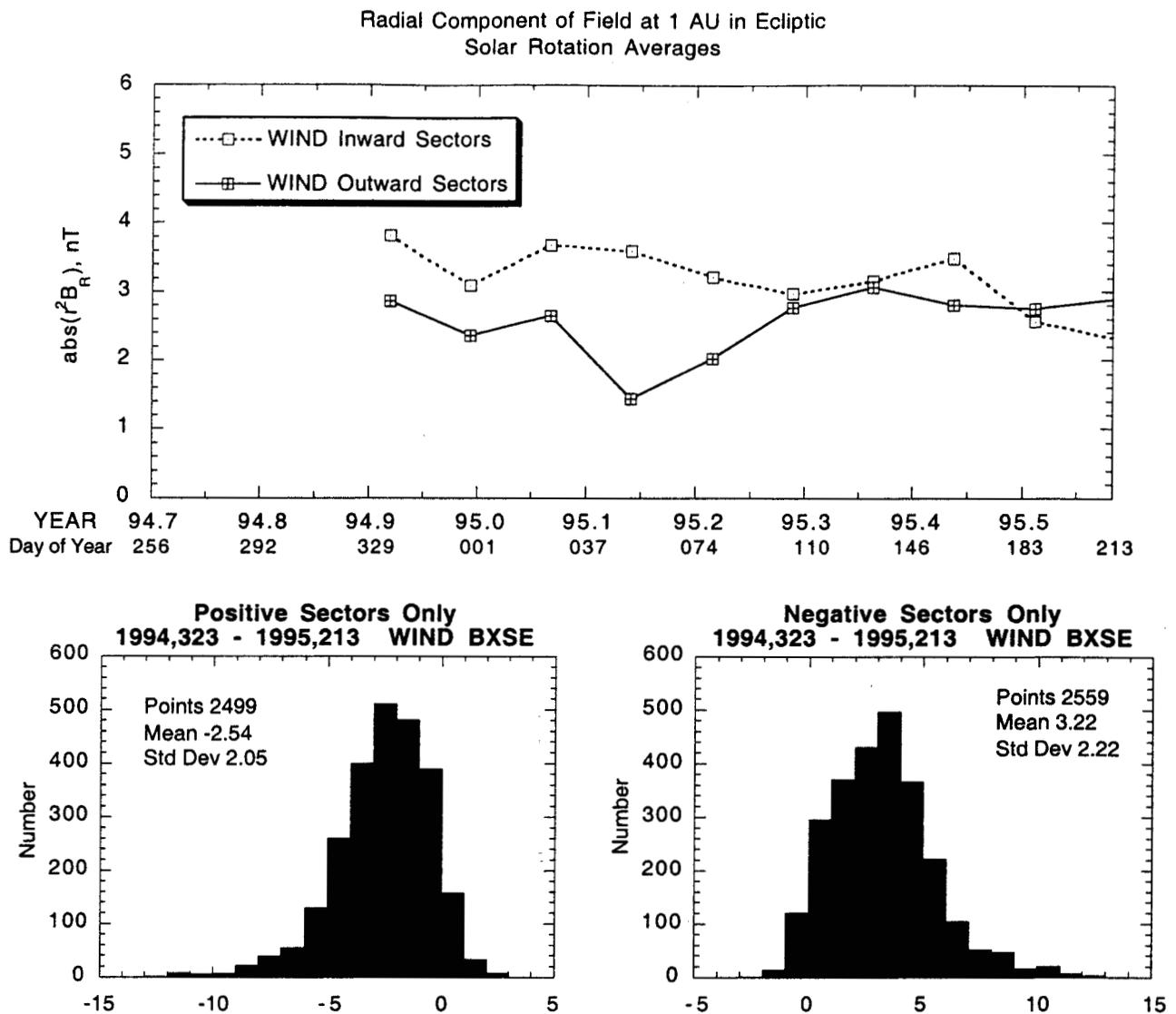


Fig. 9. WIND measurements of the radial field component in the two sectors. The upper panel shows solar rotation averages of B_R in the ecliptic for inward and outward sectors separately. During the first 5 rotations, the values in inward/south sectors are significantly larger than in outward/north sectors. This difference is eroded toward the end of the interval as the field in the north hemisphere increases. The lower panels show the probability distributions for the measurements in the two sectors (in solar ecliptic coordinates!) which are typical of in-ecliptic observations and not unusual.

An obvious test of both the temporal stability and equality of the HMF in the two sectors is provided by the in-ecliptic measurements made by IMP-8 and WIND (launched in December during the FLS) (Smith *et al.*, 1999). Figure 9 shows the magnitudes of the radial components in the two sectors averaged over successive solar rotations. The values of B_R are significantly different during the first five solar rotations differing by as much as 1 nT (and well outside possible measurement error). The radial field component is stronger in the inward sector consistent with a southward displacement of the HCS. A significant time variation is also evident with the two values of B_R becoming more nearly equal and without a persistent N/S difference by the end of the interval when Ulysses had progressed into the north hemisphere. The gradual decrease in $|B_R|$ from ≈ 4 to ≈ 3 nT is also evident in the Ulysses data in the south hemisphere.

The WIND data have been examined more closely by forming histograms of B_R throughout the interval in Figure 9. They are similar to those customarily seen in the ecliptic. Furthermore, the most probable values in the two sectors are consistent with the averages and confirm a N/S difference of ≈ 1 nT in the early portion of the interval. The WIND and IMP-8 data are also consistent. Thus, the in-ecliptic observations are consistent

with a N/S asymmetry and with a time variation that prevented the asymmetry from being apparent in the Ulysses measurements.

The existence of this asymmetry raises a number of important questions that will need to be addressed. Does the N/S asymmetry adequately account for the cosmic ray observations? What is the cause of the asymmetry? A N/S difference in the sun's global magnetic field or an asymmetry in the solar wind from the two polar caps? How prevalent is the asymmetry; how often does it occur? How long does it last? Is there a solar cycle dependence? Clearly, these Ulysses observations represent another example fulfilling the expectation that the mission would provide a new perspective on the three dimensional heliosphere.

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