# RADIAL AND AZIMUTHAL COMPONENTS OF THE HELIOSPHERIC MAGNETIC FIELD: ULYSSES OBSERVATIONS

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ABSTRACT

Two invariant associated with the Parker model of the solar wind involve the radial, $B_R$, and azimuthal, $B_T$, components of the heliospheric magnetic field, These invariants have been investigated using Ulysses data obtained at high latitudes in both the north and south solar hemispheres. The magnetic flux invariant, $r^2B_R$, is essentially independent of latitude in both hemispheres. However, comparisons with in-ecliptic IMP-8 and WIND observations reveal a small decrease with time of -6%. Average values of the second invariant, $rV_RB_T$, which is related to the heliospheric electric field, differ systematically from the Parker theory, the difference being a function of latitude that cannot be accounted for simply by a changing solar rotation period. No asymmetry in the discrepancy is found between the two hemispheres. The difference vanishes at the solar equator as shown by a comparison with the in-ecliptic measurements. These results are consistent with the average spiral angle being more radial (underwound) at high latitude than is predicted by the Parker angle and an interval has been identified in which the observed angle is approximately zero on average, This behavior contrasts with the most probable value of the invariant or the spiral angle which does agree with theory. The difference between the average and the most probable value is caused by an asymmetry in the probability distribution. This apparent reduction in average $B_T$ may bear on the long-standing issue of a "flux deficit" in the distant heliospheric field.

INTRODUCTION

Conserved or invariant quantities play a special role in physical models. They provide an observational test of their validity and of the physics underlying the models. The Parker model of the solar wind (Parker, 1963), although based on the simplest case of a radially symmetric, time-independent flow, has been remarkably successful. Nevertheless, the search continues for circumstances or spatial regimes in which discrepancies may occur. The Ulysses mission provides a unique opportunity to extend our knowledge and testing of in-ecliptic solar wind phenomena into the three-dimensional heliosphere, including the Sun's polar regions (Smith and Marsden, 1995),

In the Parker model, there are two invariant that involve the heliospheric magnetic field (HMF). One relates to the conservation of magnetic flux and states that $r^2B_R$ should be constant along a radial direction. It is not required, but commonly assumed, that $B_R$ is independent of latitude. The alternative possibility is that the strong polar cap fields leave their imprint on $B_R$ which accordingly is stronger at higher latitudes. One of the significant Ulysses findings has been that $r^2B_R$ is independent of latitude in both solar hemispheres (Smith and Balogh, 1995).

The second invariant involves the azimuthal or longitudinal component, $B_T$ or $B_\phi$, in spherical coordinates. In the Parker model, $rV_RB_T$, where $V_R$ is the radial solar wind velocity, is also constant along the radial direction. This invariant is dependent on other basic parameters, specifically, $B_R$, the angular rate of rotation of the Sun, $\Omega$, and the colatitude of the point of observation, $\theta$. Past Ulysses analyses have emphasized the alternative expression of this invariance in terms of the observed spiral angle between the radial direction and the field, i.e., Arc tan $(B_T/B_R)$ and the extent of its agreement with the Parker angle (Forsyth *et al.*, 1996; Forsyth et *al.*, 1995).

This article will address both invariant using the Ulysses data obtained recently in the two solar hemispheres. To discriminate between spatial and temporal dependence, it is essential to have baseline, in-ecliptic measurements of the HMF for comparison. Fortunately, the continuing IMP-8 measurements are now being supplemented by the more recent WIND measurements. The WIND spacecraft monitors the solar wind continuously which represents a significant enhancement of our studies,

RADIAL COMPONENT

Daily averages of $r^2B_R$ during the passage from the south to the north polar caps are shown in Figure 1 where they are plotted against time in fractions of a year with heliographic latitude shown along the top scale. The "stepwise" change in the first quarter of 1995 is the result of passing through the equator during the Ulysses Fast Latitude Scan (Smith *et al.*, 1995). The radial field component is negative in the south and positive in the north hemispheres as expected. Mean values between -80° and -40° and from +40° to +80° are shown. They are slightly different, -3.23 as compared to 3.05 nT (AU)*. The difference is significant and can be shown to be caused by a small time variation occurring over the interval of -1 year.

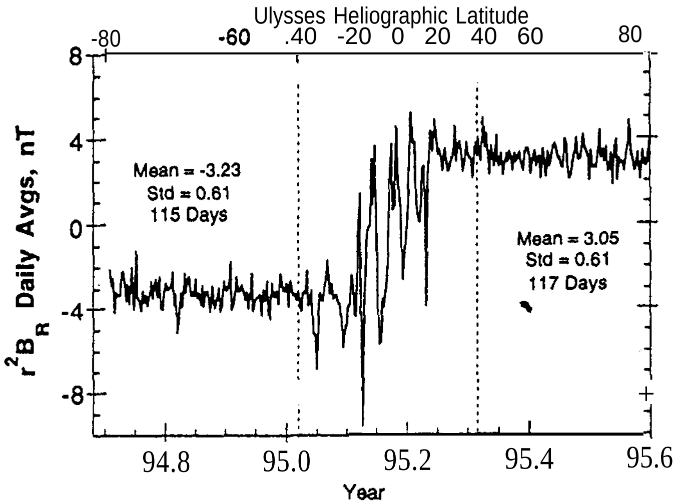



Fig. 1. Radial field component pole-to-pole

The most obvious feature of Figure 1 is the constancy of $r^2B_R$ over the full range of latitudes. Such a result is consistent with $B_R$ being attributable only to the current in the Heliospheric Current Sheet (HCS), e.g., see the derivation in Smith *et al.* (1 978), Since, in plasma physics, currents are considered to be caused by stresses and it is customary to derive them from the resulting magnetic field (by way of $\nabla XB$), it is more appropriate to say that a uniform radial field component that reverses sign between heliospheres gives rise to the Current Sheet. Presumably, this uniformity is achieved much nearer the Sun than the location of Ulysses. We have interpreted this condition as being caused by magnetic stresses near the Sun, associated with the strong polar cap magnetic fields, which push the solar wind equatorward until a uniform field is produced and equilibrium is achieved (Smith and Balogh, 1995); (Suess and Smith, 1996). The spreading of the wind from the south polar coronal hole into the observed solid angle occupied by the fast solar wind implies an expansion by a factor of -5. On this basis, the magnetic field at the Sun's pole is inferred to have a strength of ~7 Gauss.

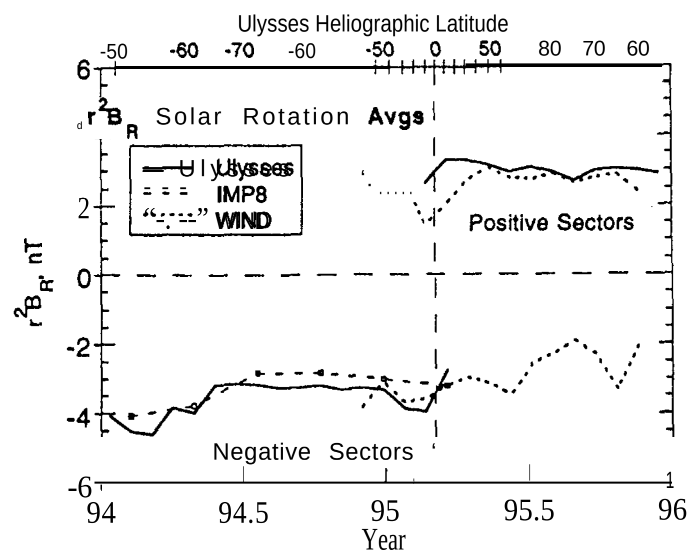



Fig. 2. Radial field component in the ecliptic and at high latitude

To avoid confusion between spatial and temporal variations, we have compared the Ulysses measurements with those of in-ecliptic spacecraft, IMP-8 and, more recently, WIND. The in-ecliptic data were resolved

, into the two sectors and measurements in each sector were averaged separately, This comparison is shown in Figure 2, which is similar to Figure 1 but covers a longer time interval and now shows solar rotation averages at the three spacecraft. The three data sets agree within the limits of accuracy and the possible presence of time variations. Over the same intervals in which the averages in Figure 1 were computed, the IMP-8 plus WIND data average in negative sectors is -3,12 nT while, in positive sectors, the WIND average is 2,89 nT. Thus, the Ulysses and in-ecliptic averages agree within 0.11 and 0.16 nT, i.e., < 5%, Furthermore, the magnitudes of the averages in the negative and positive sectors differ by -0,16 nT at Ulysses and -0.23 nT in the ecliptic.

Since IMP-8 and WIND sample both positive and negative sectors in a given solar rotation, the changing magnitudes of $B_R$ with time can be seen directly in those data. It is for this reason that the WIND values in negative sectors have been extended into the right half of Figure 2. In spite of the shorter scale temporal variations, the gradual decrease in $B_R$ (-) is apparent. The average of the WIND measurements with Ulysses in the north hemisphere is -3.0 nT which agrees with the Ulysses average. Because of time variations, the standard deviations associated with these averages are large, typically 0,6 nT, We conclude that the apparent differences in Figure 2 between negative and positive sectors are actually caused by a small decrease in $B_R$ of -0.2 nT between 1994 and 1995 and are not associated with a north-south asymmetry.

There have been reports of such an asymmetry (Luhmann et *al.*, 1988). Figure 3, taken from a recent paper by Burton *et al.* (1996), shows $B_R$ values in the two sectors as a function of heliomagnetic latitude (the latter being derived from the Stanford University neutral line contours published regularly in Solar Geophysical reports). The five panels cover the years from 1984-88 (the previous solar minimum). Measurements made in the vicinity of the Current Sheet or near magnetic polarity reversals have been avoided. As can be seen, and as borne out by the analysis in Burton et *al.* (1996), there is no evidence of a north-south asymmetry in *these* data.

## AZIMUTHAL COMPONENT

Parker's theory for a radial symmetric solar wind leads to an invariant that is closely related to the spiral angle. Thus,

(1) $$\tan \phi_P = B_T/B_R = - \Omega\, r \sin \theta / V_R$$

or

(2) $$r\, V_R\, B_T = - \Omega \sin \theta\, r^2 B_R$$

Considered as a function of distance, at a given 9, $rV_RB_T$ = constant. Physically, this invariance is a re-statement of the basic physical principle underlying the formation of the spiral angle, namely, that the steady electric field vanishes in the solar wind frame because of its very large electrical conductivity. Radial currents are established that Produce a $B_T$ such that $V_R B_T$ cancels the E field,

(3) $$E_N = -\Omega\, r \sin \theta\, B_R$$

in inertial space caused by the coronation of the magnetic field with the Sun. It is seen that $rV_RB_T$ represents a voltage and that the integral of the voltage over a closed contour vanishes in accordance with $V = -d\Phi/dt = 0$. From these relations, it also follows that $B_T$ and $E_N$ are both proportional to r-*.

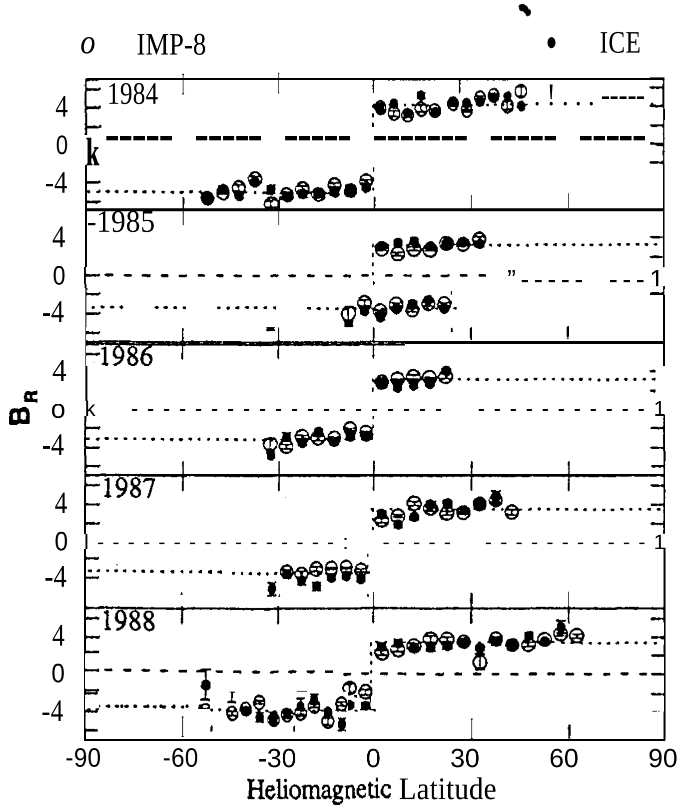



Fig. 3. Radial field component above and below the Heliosphere Current Sheet

The analysis of $rV_RB_T$ is complementary to that of the observed spiral angle, $\phi_B$, which has been intensively studied in the Ulysses data (Forsyth *et al.* 1996; Forsyth *et al.* 1995). It has some potential advantages that stem from the appearance of the ratio, $B_T/B_R$, and of the inverse tangent in the expression for the spiral angle.

, It is customary to take the ratio of the averages, $<B_T>/<B_R>$, the brackets indicating average values, instead of the average of the ratio, i.e.. $<B_T/B_R>$. A further concern is the nonlinear character of the inverse "tangent, especially for large values of-the angle.

The questions to be investigated are the following. Is the dependence of $rV_RB_T$ on sin $\theta$ or, alternatively, on cos $\delta$ ($\theta$ = colatitude, $\delta$ = latitude) evident? Is the invariant otherwise independent of $\delta$ or r (recalling that $r^2B_R$ is invariant as we have seen)? Can departures of $\Omega$ from its equatorial value, $\Omega_0$, be discerned, especially at high latitude?

We begin by plotting $-<rV_RB_T>/\Omega_0$ r. $<r^2B_R>$ against cos $\delta$ with the results shown in Figure 4. The subscript zero implies the equatorial value of $\Omega$ and a radial distance of 1 AU so that $\Omega_0$ r. = 419 km/s. Each point corresponds to an average over a solar rotation period of 25 days. Observations in the two hemispheres are shown separately, The basic equation implies a linear dependence on cos $\delta$ as represented by the solid line with slope = 1. The least squares linear fits are shown by the dashed lines and, while the data agree with a linear dependence reasonably well, the observed slopes in both hemispheres are 0,76 and not 1.0. Again, there is no evidence of a north-south asymmetry. What is the cause of the systematic departure in slope?

Before pursuing this important question, it should be noted that one of 'the points in the north hemisphere, near cos $\delta$ = 0.33, is perilously close to zero. We have inspected a plot of the spiral angle to confirm this observation and to determine where/when it occurred, Figure 5 shows $\phi_P$ (dashed) and $\phi_B$ (solid) throughout most of 1995 with maximum latitude occurring near the center of the plot (see the top scale), The observed angle does increase to approximately zero during the interval

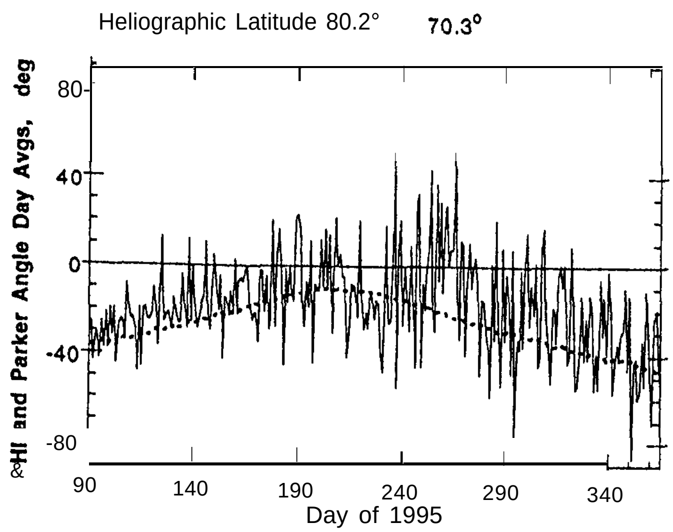
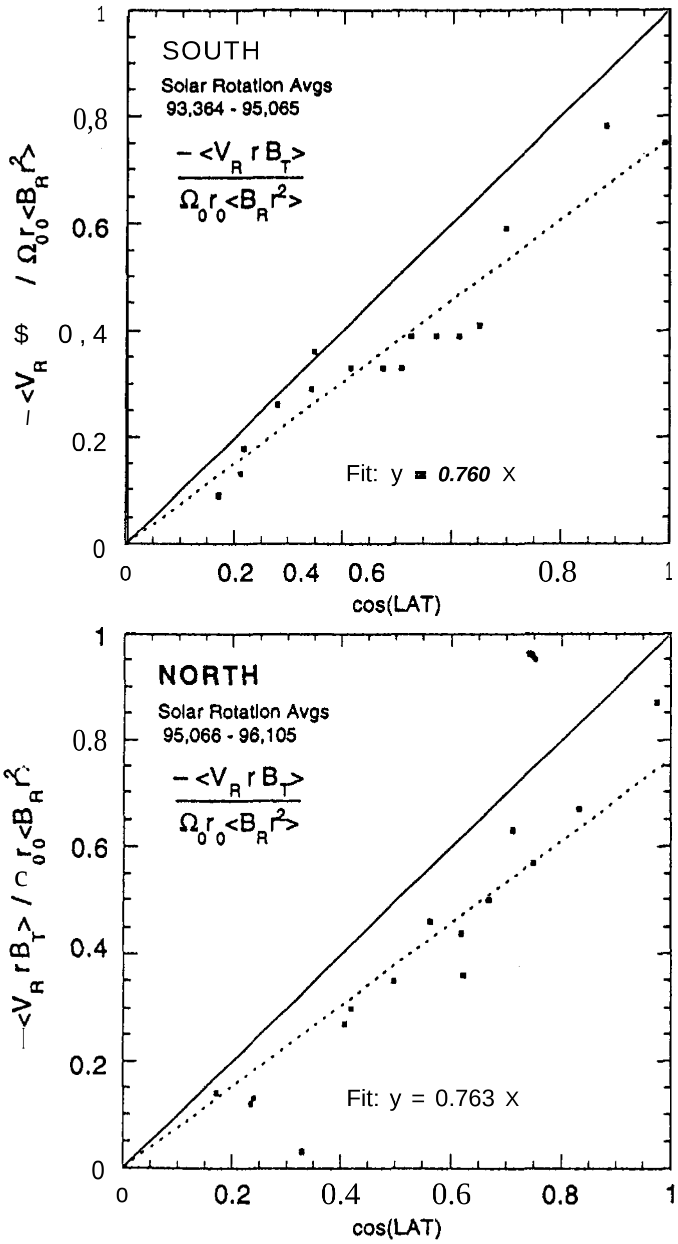



Fig. 5. The average spiral in the north hemisphere




Fig, 4. Normalized invariant, $rV_RB_T$, as a function of heliographic latitude

between days 250 and 280, The spacecraft was not at maximum latitude but had descended to -70° at that time, An obvious interpretation is that $\Omega$ = O for these observations or that the field lines being sampled at -70° originate at or near the Sun's rotation axis, If true, this observation implies a latitudinal displacement of the field lines by -20°. This result is interesting in view of recent proposals that predict such displacements in latitude (Fisk 1996).

It is also noteworthy that the average value of the spiral angle disagrees with the Parker angle (Forsyth *et al.*, 1995, 1996). The observed value is less than $\phi_P$ in agreement with Figure 4. On the other hand, the most probable value of the observed angle at high latitudes corresponds to the Parker value within reasonable statistical limits. Clearly, the averages and modes are exhibiting a different dependence,

To return to the discrepancy apparent in Figure 4, a possible interpretation is that it results from the dependence of the Sun's angular velocity on latitude, i.e., on $\Omega(\delta)$. Figure 6 addresses this possibility by showing the invariant, now divided by cos $\delta$ to eliminate this dependence, as a function of latitude. The smooth dashed curve is one of several that have been inferred by studying the rotation period of sunspots and other features as a function of latitude (Newton and Nunn, 1951). The equation used is given in the figure. It is evident that most of the observations lie significantly below this curve so that it represents a poor fit to the data. A clear dependence on latitude is, in fact, not evident. but if this interpretation is pursued it would imply rotation periods at high latitudes of -50 days or much larger than is commonly supposed.

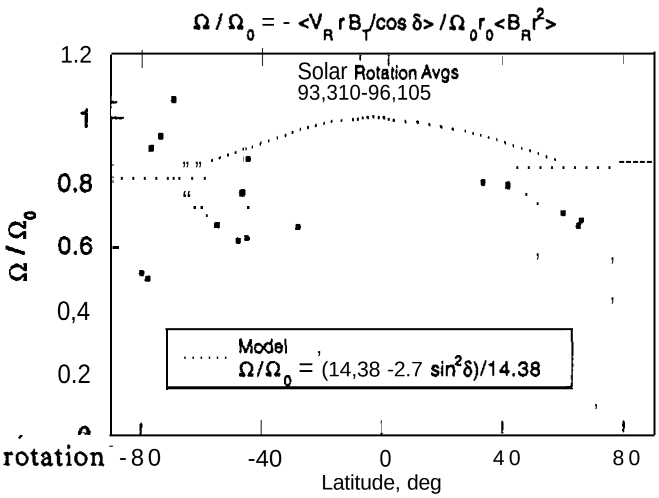



Fig. 6. Normalized invariant, $rV_RB_T$, as a function of latitude

An alternative explanation is that the discrepancy is a function of radial distance rather than latitude. Figure 7 shows the same data as in Figure 6 but now plotted vs. heliocentric distance (range) in AU. The visual impression of a lack of correlation is reinforced by the straight line fit which yields a small correlation coefficient of only 0.12. Thus, it is unlikely that the discrepancy, whereby $rV_RB_T$ has a value approximately 3/4 of what it should be, depends on either latitude or distance. Can it be an artifact of some sort?

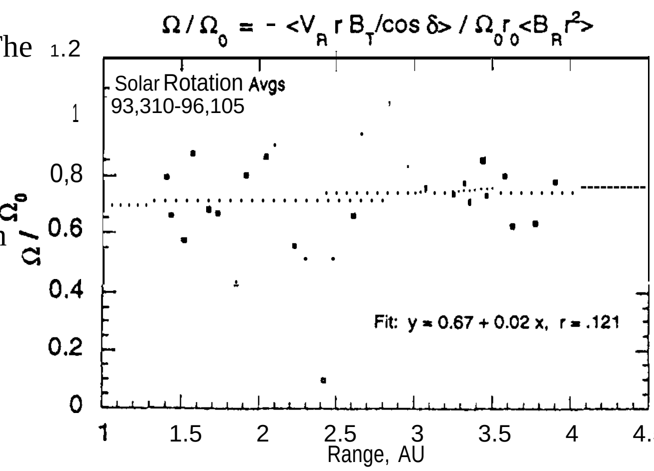



Fig. 7. The normalized invariant as a function of radial distance

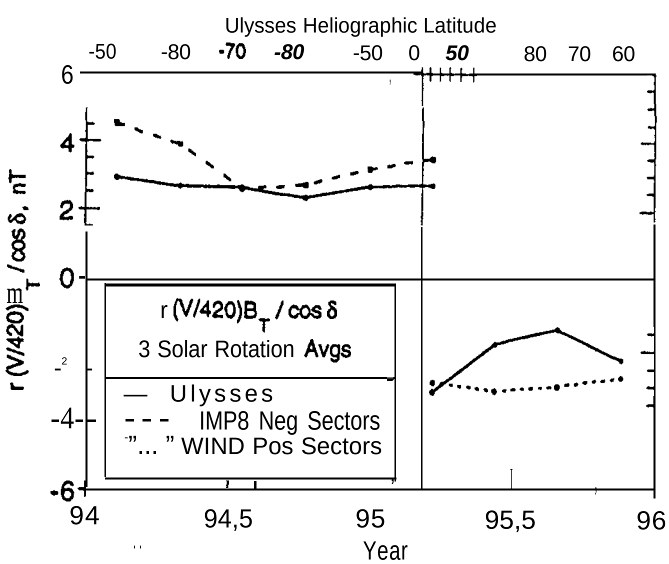



Fig. 8. Normalized invariant in the ecliptic and at high latitude

Another test that can be applied is a comparison of the Ulysses observations with the in-ecliptic data available from IMP-8 and WIND. The same basic invariant calculated at both locations and averaged over three successive solar rotations to suppress short term variability is shown in Figure 8. Except for two points, with Ulysses near -70° and 10° latitude, the Ulysses observations are systematically lower than the in-ecliptic observations. Several of the differences are quite large, -1.0- 1.5 $nT(AU)^2$.

The question of which values are "correct" can be tested by comparing with the right-hand side. of the appropriate equation,

(4) $$r V_R B_T/\Omega_0 r_0 \cos \delta = - \Omega/\Omega_0 \langle r^2 B_R \rangle.$$

Assuming $\Omega/\Omega_0 = 1$, the parameter plotted in Figure 8 should equal $-r^2B_R$. The interval covered in the figure is the same as in Figure 2 so that the averages differ slightly from those in Figure 1. The Ulysses average in Figure 2 over negative (positive) sectors is -3.57 (3.00) $nT(AU)^2$. The combined IMP-8 and WIND average of $r^2B_R$ in negative sectors is -3.31 nT and the WIND average in positive sectors is 2.59 nT.

These values can be compared with the averages of $rV_RB_T/\cos$ S in Figure 8, The Ulysses averages are 3.47 and -2.16 nT in the south and north hemispheres. The in-ecliptic averages are 2.72 and -2,96 nT, respectively. Thus, the ratios $\langle -r^2B_R \rangle : \langle rVB_T/\cos \delta \rangle : \langle rVB_T \rangle$ are +3,6:2,7:3.5 (south) and -3.0: -2.2:-3.0 (north). The values of $\langle rVB_T \rangle$ in the ecliptic agree closely with $\langle r^2B_R \rangle$. The values of $\langle rVB_R/\cos \delta \rangle$ at Ulysses, on the other hand, are significantly smaller by 0.9 and 0,8 nT.

To pursue this result further, we have inspected the probability distributions of the values of the invariant at Ulysses as shown in Figure 9. The south distribution covers approximately one year during which the spacecraft travelled from -50° to -80.2° to -37°, The north distribution extends over a comparable range of time and latitude, The distributions are very revealing. In both hemispheres, the most probable values agree with the average values of $r^2B_R$ of -3,5 and 3.1 $nT(AU)^2$. However, the average values are both smaller, i.e., 2.5 and -1.9 $nT(AU)^2$, respectively, consistent with Figure 8. The reason for the differences between the most probable and average values is an asymmetry in the distributions such that there is an excess of low values near zero, These results and, in particular, the "asymmetry in the probability distributions, parallel those found in the complementary studies 'of the spiral angle.

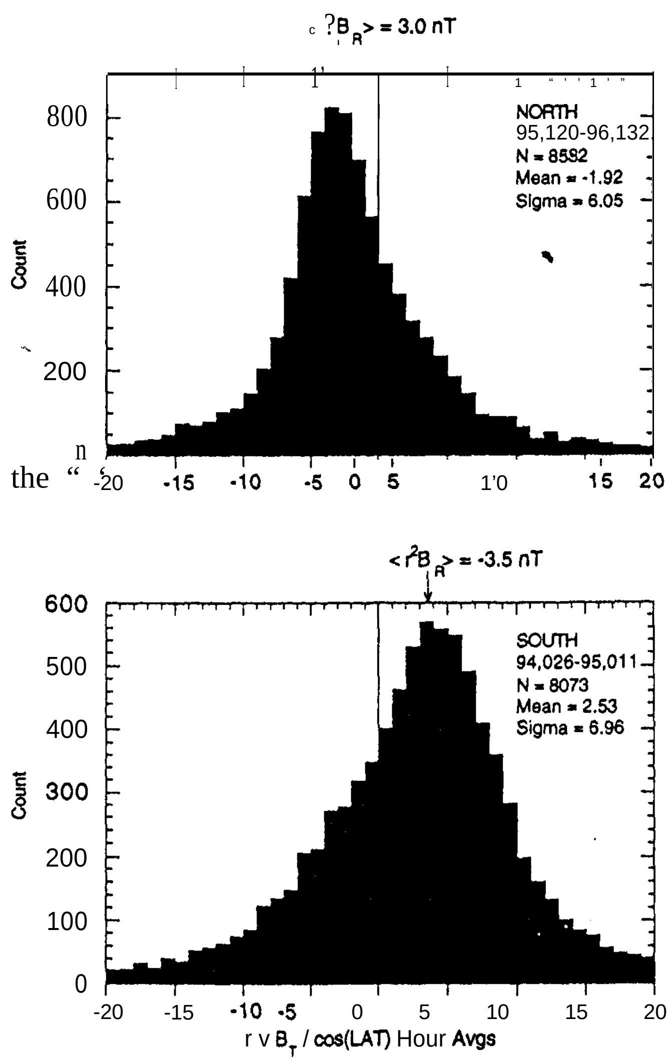



Fig. 9. Probability Distributions of Normalized Invariant in North and South Hemispheres

The differences are too large to be explained by measurement errors. The absolute accuracy of the Ulysses measurements as determined in-flight, taking advantage of the spacecraft spin, ensures that the measurements are correct to less than 5 pT, not hundreds of pT. Furthermore, any such error would have to change sign from one hemisphere to the other, an unlikely event. Finally, there is no evidence in the measurements of a significant error in the much smaller $B_R$ component.

We conclude that the discrepancy is caused by an effect not included in the Parker model, Since the latter is time independent, some aspect of solar wind dynamics may be involved. In the past, we have speculated that such discrepancies in the spiral angle are attributable to the large amplitude Alfvén waves that characterize the Ulysses data at high latitude. There are other possibilities, of course, such as the influence of high latitude coronal mass ejections (CMEs), pressure balance structures, etc. However, whatever the cause may be, it is unknown at present. Further study will be required to isolate and identify it.

It is worth noting that a systematic discrepancy in $B_T$ could help explain the so-called "flux deficit" inferred in the outer heliosphere on the basis of pionee r. 1 0, 1 1 data (Winterhalter *et al.* 1990) (but not confirmed by the Voyager analysis (Burlaga and Ness, 1993)). on e of the possible interpretations has held that enhanced equatorial pressure causes a divergence of $B_R$ away from the equator (Pizzo and Goldstein, 1987; Suess *et al.*, 1985), Clearly, such an interpretation is inconsistent with the Ulysses finding that $r^2B_R$ is constant.

It is only the outstanding accuracy of the Ulysses Vector Helium Magnetometer that has permitted the measurement of the very weak radial field component at and beyond a few AU (at 5 AU, $B_R \cong 3.5/52$ = .014 nT = 14 pT). The less accurate Pioneer and Voyager comparisons with the Parker model were not based on measurements of $B_R$ but on measurements of $B_T$ (or B). Therefore, a deficit in $B_T$ could be interpreted as implying that magnetic flux is not conserved (since $r^2B_R$ is proportional to $B_T$ in the above equations). Clarification of this issue provides another reason for continuing to study $rV_RB_T$.

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