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# The underlying Parker spiral structure in the Ulysses magnetic field observations, 1990-1994

R. J. Forsyth,[1] A. Balogh,[1] E. J. Smith,[2] G. Erdös,[3] and D. J. McComas[4]

**Abstract.** The fundamental aim of the Ulysses space mission is to extend our understanding of the heliosphere into three dimensions. By April 1994 the spacecraft had reached a heliographic latitude of 60°S. Hourly averages of the Ulysses heliospheric magnetic field observations have been analyzed to determine to what extent the underlying field direction within 60° of the heliographic equator can be described by the Parker spiral model. At all latitudes from near the ecliptic southward to 60°S, the most probable value of the azimuthal orientation of the field lines remained in approximate agreement with the Parker model. Once Ulysses passed southward of the maximum latitude of the heliospheric current sheet at about 30°S it became possible to study the distribution of the azimuth angle in purely inward polarity southern hemisphere fields without the confusion between the northern and southern hemisphere sectors. This distribution is revealed to be highly asymmetric with a greater probability of observing field lines with an azimuth angle less tightly wound than the most probable angle. Comparison with near-ecliptic data showed a similar asymmetry in inward polarity field sectors while in outward polarity sectors there was an asymmetry in the opposite sense. We suggest that the asymmetry in the >30°S azimuth angle distribution arises due to the presence of long-period radially outward propagating Alfvén waves in the solar wind flows originating from the southern polar coronal hole. In addition, from studying the meridional (north-south) orientation of the field lines we find that at south heliographic latitudes within about 25° of the equator there is a tendency in the Ulysses data set for the field lines to be on average deflected equatorward of their expected direction, most likely due to flow deflections associated with the interaction of high- and low-speed solar wind streams.

## Introduction

Over the past 3 decades several spacecraft have investigated the large-scale structure of the heliospheric magnetic field (HMF) close to the ecliptic plane (see, for example, the review by *Smith* [1989]). However, the ongoing Ulysses mission [*Wenzel et al.*, 1992] is the first to perform such studies over a large range of heliographic latitudes. Even before the first of these space missions was flown, *Parker* [1958] had developed a simple model suggesting a radially expanding solar wind with an embedded spiral magnetic field. This is based on the assumptions that the magnetic field lines are frozen in to the highly conducting radially outflowing solar wind and that the field lines are aligned in the radial direction at the source surface near the Sun. In a frame of reference corotating with the Sun the frozen-in condition means that the field lines will thus always be parallel to the solar wind velocity vector and equivalently that there will be zero electric field in this frame. Transforming into a noncorotating frame leads to the magnetic field being wound up into a spiral in the plane of the heliographic equator, the field direction becoming increasingly azimuthal with increasing radial distance from the Sun. As one moves to higher heliographic latitudes one would expect the spiral to gradually unwind until over the solar poles open radially outward field lines would be expected. Alternatively, at any colatitude $\theta$, the field lines can be viewed as being wrapped round the surface of a cone of half angle $\theta$. That the field directions predicted by this model are correct to first approximation close to the ecliptic plane was confirmed originally at 1 AU by *Ness and Wilcox* [1964], over a greater range of heliocentric distance by (among others) *Thomas and Smith* [1980] and *Burlaga et al.* [1982], and specifically for the in-ecliptic cruise of Ulysses taken as a whole by *Balogh et al.* [1993]. Ulysses is obtaining magnetic field measurements at heliographic latitudes up to 80° in both solar hemispheres and is therefore ideally suited to study how well the spiral model extends into three dimensions. By April 1994 Ulysses had reached a latitude of 60°S on its way to the first south polar pass. The purpose of this paper is to compare observations of the large-scale magnetic field direction over the whole mission up to April 1994 with the direction predicted by the simple spiral model. At heliographic latitudes greater than 60°S, not discussed in this paper, apparent departures from a simple model were observed, which required further analysis and have become the subject of a further paper [*Forsyth et al.*, 1995].

[1]The Blackett Laboratory, Imperial College, London, United Kingdom.
[2]Jet Propulsion Laboratory, Pasadena, California.
[3]KFKI Research Institute for Nuclear and Particle Physics, Budapest. Hungary.
[4]Los Alamos National Laboratory, Los Alamos, New Mexico.



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## Observations and Analysis

The magnetic field measurements used in this study were obtained by the magnetometer experiment on Ulysses. This is a dual-sensor magnetometer which has been described in full by *Balogh et al.* [1992]. We also make use of hourly averages of the solar wind velocity measured by the Ulysses plasma instrument [*Bame et al.*, 1992]. The range of heliocentric distance and heliographic latitude traversed by Ulysses during the period under study is shown in Figure 1 along with an indication of the time spent traversing each region. During the "in-ecliptic" cruise from October 1990 to February 1992 (the Jupiter flyby) the spacecraft travelled from 1 out to 5.4 AU with heliographic latitude slowly changing from 5°N to 6°S. From February 1992 to April 1994 heliographic latitudes from 6°S to 60°S were steadily sampled while the heliocentric range decreased, initially relatively slowly, to 3.2 AU.

In the analysis that follows we have worked in the heliospheric *RTN* coordinate system. This spacecraft centred spherical coordinate system is defined by an *R* axis pointing radially antisunward, a *T* (transverse) axis parallel to the solar equatorial plane, positive in the direction of solar rotation, and an *N* axis completing the right-handed system. Thus at any point in space the *R*, *T* and *N* directions are always perpendicular to each other and the *R-T* plane is inclined to the heliographic equatorial plane by an angle equal to the heliographic latitude of the spacecraft. As this study is concerned with the field direction, referring to Figure 2, we discuss the azimuth angle $\phi_B$ that the projection of the HMF vector onto the *R-T* plane makes with the *R* axis in a right-handed sense, and the meridional (or north-south) angle $\delta_B$ of the HMF with respect to the *R-T* plane. These angles are defined in terms of the field components by

$$\tan\phi_B = B_T/B_R \tag{1}$$

$$\sin\delta_B = B_N/|\mathbf{B}| \tag{2}$$

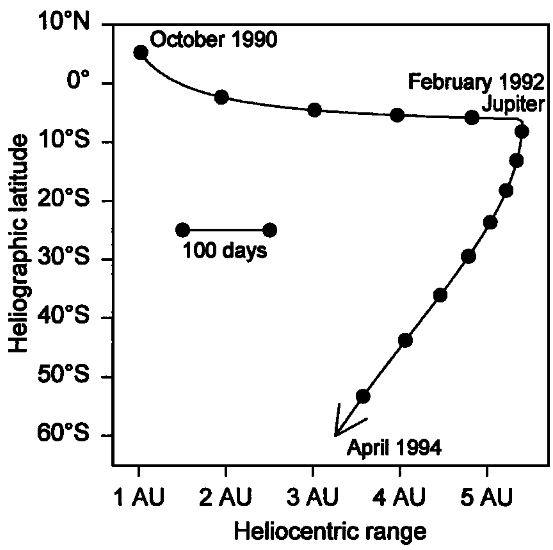


**Figure 1.** The trajectory of Ulysses from October 1990 to April 1994 plotted against heliocentric distance and heliographic latitude. The symbols superimposed on the trajectory represent 100-day intervals to indicate the rate at which Ulysses traversed each region.

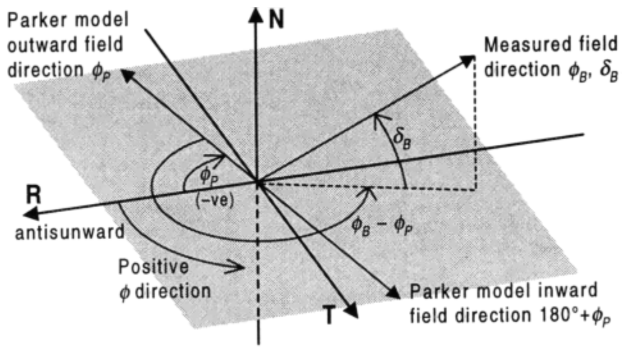


**Figure 2.** Definitions of the azimuth angle deviation $\phi_B-\phi_P$ and meridional angle deviation $\delta_B$ with respect to the *RTN* coordinate system. The measured field direction is drawn for a sunward pointing field line presently typical of the southern solar hemisphere. In this reference system the predicted azimuth angle $\phi_P$ of an outward polarity field line is a negative quantity.

From Parker's model it is straightforward to deduce the azimuth angle $\phi_P$ that the tangent to the ideal Parker spiral magnetic field makes with the radially outward direction at a position in interplanetary space specified by radial distance $r$ and heliographic latitude $\delta$. This is given by

$$\tan\phi_P = \frac{v_\phi - \Omega r\cos\delta}{v_r} \tag{3}$$

where $\Omega$ is the solar rotation rate and $v_r$ and $v_\phi$ are the radial and azimuthal components of the solar wind velocity. Note that since $v_\phi$ is usually small enough to be ignored to first approximation, (3) implies that the angle $\phi_P$ is negative. In the coordinate system described above and referring to Figure 2, a magnetic field vector with a direction in agreement with the Parker model will have either $\phi_B = \phi_P$ in a region of outward polarity field (outward sector), that is north of the heliospheric current sheet in the current solar cycle, or $\phi_B = 180° + \phi_P$ in a region of inward polarity field. In both regions Parker's model predicts that an ideal magnetic field vector will have a meridional angle $\delta_B = 0°$ with respect to the *R-T* plane.

The basic data set used in our analysis consists of hourly averages of the Ulysses HMF measurements transformed into the *RTN* coordinate system. This data set covers the period from instrument turn-on on October 25, 1990, through to data ending on April 17, 1994, when the spacecraft crossed 60°S. We use (1) and (2) to calculate $\phi_B$ and $\delta_B$ from the hourly averaged magnetic field components. The azimuth angle $\phi_P$ expected from Parker's model is calculated from (3) using hourly averages of the radial component of the solar wind velocity $v_r$, along with $r$ and $\delta$ values obtained from Ulysses trajectory data. The value used for the solar rotation rate $\Omega$ was that equivalent to a rotation period of 25.38 days. We treat the azimuthal component of the solar wind velocity $v_\phi$ as insignificantly small in this analysis, which is not inconsistent with the data.

Figure 3 shows the expected value of the spiral angle at Ulysses, from October 1990 to April 1994, obtained from the above calculation. We have plotted $-\phi_P$ (see Figure 2), as this gives the normally quoted numerical values for the spiral angle on the vertical axis, increasing from close to 45° near

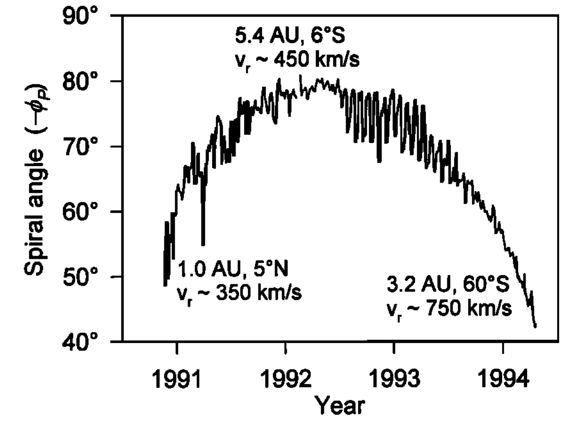


**Figure 3.** The expected spiral angle of the heliospheric magnetic field at Ulysses calculated using the position of the spacecraft and the solar wind velocity measured by Ulysses.

1 AU to more than 80° near 5 AU. Since we have included the measured solar wind velocity in our calculation of $\phi_P$, Figure 3 shows a modulation due to variations in $v_r$ superimposed on the smooth variation of the spiral angle with spacecraft position that would have been obtained using a constant solar wind velocity. From October 1990 to February 1992 we see the expected spiral angle increasing with radial distance. From then on the expected spiral angle decreases, partly as a result of the now decreasing radial distance, but mainly due to the increasing heliographic latitude. The effect of the changing solar wind velocity is to reduce the spiral angle during intervals of higher velocity. Thus the interval of high-speed solar wind resulting from the solar events of March 1991 shows on this plot as a reduction of the expected spiral angle. Similarly, the period from late 1992 into early 1993 when the solar wind speed was strongly modulated at the solar rotation period by a high-speed stream emanating from a northward extension of the southern polar coronal hole [*Bame et al.*, 1993] has a corresponding effect on the expected spiral angle.

Taking the Ulysses field azimuth angle measurements $\phi_B$, we calculate $\phi_B-\phi_P$ (Figure 2), the field azimuth angle with respect to the expected outward pointing spiral direction. In the ideal case $\phi_B-\phi_P$ will have values either of 0° or 180° so that the outcome of this analysis is that the deviations in our values of $\phi_B-\phi_P$ from 0° or 180° and the deviations of $\delta_B$ from 0° represent respectively the azimuthal and meridional angular deviations from the expected Parker spiral field direction. Figure 2 has been drawn to be representative of the magnetic field configuration prevailing in the southern hemisphere during the 1990-1994 time period discussed in this paper. The magnetic field vector is directed inward toward the Sun so that $\phi_B-\phi_P$ should ideally be 180°. Values of $\phi_B-\phi_P$ greater than expected are indicative of field lines less tightly wound than the model spiral field (such as illustrated) while values less than expected are indicative of field lines more tightly wound than the model. In interpreting the direction of field line deflections indicated by positive and negative values of $\delta_B$, note must be taken of the difference of the geometry between outward and inward polarity magnetic fields as shown in Figure 4. This figure shows that in both the outward fields of the northern hemisphere and the inward fields of the southern hemisphere, positive deflections of $\delta_B$ are indicative of field lines being deflected poleward of the *RT* plane as one looks out from the Sun while negative deflections of $\delta_B$ are indicative of field lines deflected equatorwards of the *RT* plane. This association would be reversed in alternate solar cycles when the magnetic field polarity north and south of the current sheet is reversed.

Following previous authors [e.g., *Thomas and Smith*, 1980; *Burlaga et al.*, 1982] we present our results in the form of histograms. The azimuthal angle deviations $\phi_B-\phi_P$ are binned into 10° intervals and the meridional angle deviations $\delta_B$ are binned into 5° intervals. The histograms have been produced for three different stages of the mission: (1) for the in-ecliptic cruise from launch up to the Jupiter flyby, (2) for the first part of the out-of-ecliptic phase of the mission from the time of the Jupiter flyby up to a latitude of 30°S, the latitude beyond which Ulysses no longer encountered the heliospheric current sheet [*Smith et al.*, 1993] and (3) for the out-of-ecliptic phase where the latitude of the spacecraft increased from 30°S to 60°S during which Ulysses continually sampled the inward pointing fields of the southern solar hemisphere.

We also wished to assess whether there were any underlying trends with time or position (radial or latitudinal) in the values of $\phi_B-\phi_P$ and $\delta_B$ contributing to these histograms. The advantage of the histograms accumulated over long time periods is that parameters deduced from them have a high statistical validity. However, if there is any underlying trend it will be hidden or could act to make the longer period distribution appear wider than a shorter period one. Distributions accumulated over shorter time periods are required to look for these trends but have the disadvantage that the smaller number of contributing observations reduces the statistical validity of deduced mean and most probable values. We found that a reasonable compromise was, when searching for trends, to look at distributions accumulated over a time corresponding to three solar rotation periods. For this purpose the solar rotation period was taken to be 27 days for the in-ecliptic cruise, as this was found to be a good approximation when the solar wind travel time and the increasing distance of Ulysses from the Sun were taken into account. Once Ulysses began travelling out of the ecliptic its distance from the Sun changed relatively slowly, and a 25.5-day solar rotation period was found to be a reasonable approximation.

A possible criticism of our analysis is that in the results as presented we have not attempted to eliminate time intervals when coronal mass ejections (CMEs) may be perturbing the field directions measured at Ulysses. In fact, this was attempted using a preliminary Ulysses CME list (J. L. Phillips,

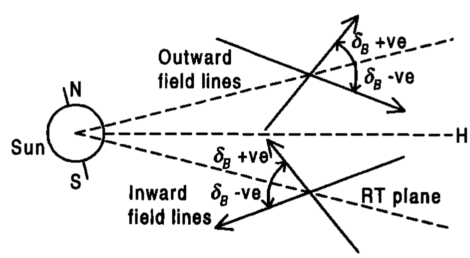


**Figure 4.** A schematic view in a meridional plane of how positive or negative values of the meridional angle $\delta_B$ correspond to poleward or equatorward deflections of field lines as they come out from the Sun, depending on whether outward (currently north of the heliospheric current sheet, HCS) or inward polarity field lines are being observed.

private communication, 1994) and was found to make no major change to the results presented below apart from increasing the error estimates due to the reduced number of observations used in the analysis.

## Results

We first describe the results for the azimuthal angle distributions shown in Figure 5. In all cases the most probable values of $\phi_B - \phi_P$ lie within a single 10° bin width of 0° or 180° indicating a good overall agreement with the Parker model over the full period studied. To facilitate a more detailed comparison some statistics of the distributions are presented in Table 1. The most probable values and mean values (with standard errors) of each distribution are given relative to the expected values of 0° or 180° and also the percentages of the values lying to either side of 0° or 180°. The estimate of the most probable value and its error were obtained by a procedure which reduces the bin widths of the distributions to the point where the most probable value just remains unambiguous.

It is clear from Figure 5 and Table 1 that the distributions are not symmetrical about 0° and 180°. For Figures 5a and 5b, northern hemisphere fields have distributions with negative mean values and correspondingly have a greater percentage of observations less than the expected azimuthal angle of 0°. This corresponds to a higher percentage of observations with larger azimuthal components relative to the radial component ("more tightly wound") than the expected spiral field. On the other hand, southern hemisphere fields have positive mean values and a higher percentage of observations with a smaller azimuthal component ("less tightly wound") than the expected spiral field.

In Figures 5a and 5b (cases (a) and (b)) the wings of the distributions of northern and southern hemisphere azimuthal angles overlap. However, Figure 5c (case(c)) allows us to study the full spread of the southern hemisphere distribution. We can see that there are a significant number of observations with azimuthal angles greater than 270° that wrap round to the left-hand side of the plot and would otherwise have been included with northern hemisphere fields. Because of this, when the mean of the distribution is taken, we obtain a value of 13.55°, which is significantly different from the most probable value. Fifty-eight percent of the observations have azimuthal angles greater than the expected spiral angle with which the observed most probable value agrees within our error estimate. This means that there is a greater probability of

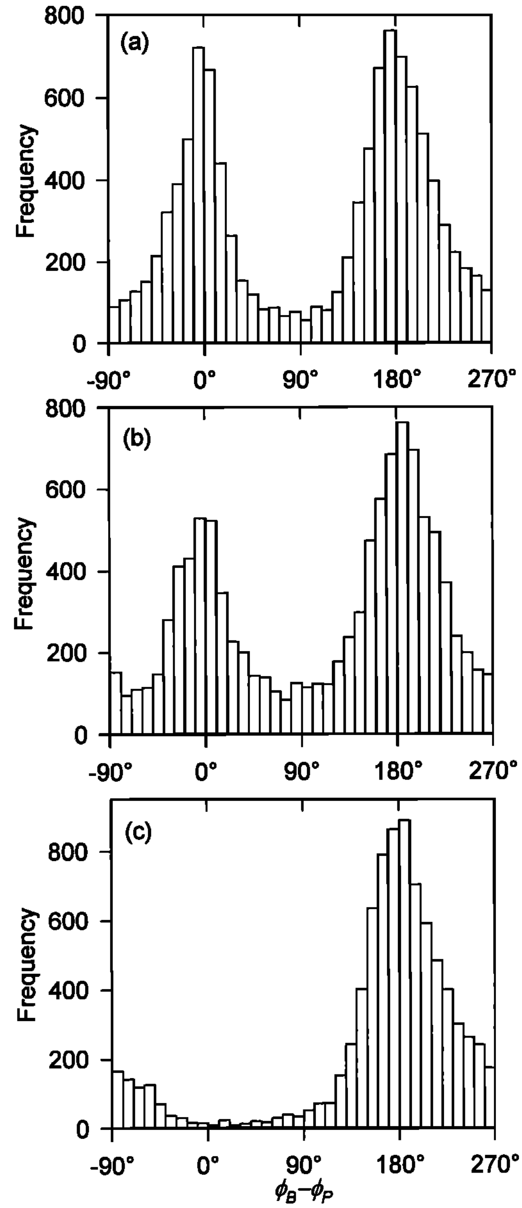


**Figure 5.** Histograms of the deviation in azimuth angle, $\phi_B - \phi_P$, from the expected Parker model magnetic field direction binned into 10° intervals for (a) the in-ecliptic cruise phase of the Ulysses mission, (b) the out-of-ecliptic phase for heliographic latitudes between 6°S and 30°S, and (c) latitudes between 30°S and 60°S.

**Table 1.** Statistics of Azimuthal Angle Deviations From the Expected Parker Model Direction

| Latitude Range | Most Probable Value, deg | Mean ± Standard Error, deg | < 0°, % | > 0°, % | < 180°, % | > 180°, % |
|---|---|---|---|---|---|---|
| *Outward (northern hemisphere) fields* | | | | | | |
| (a) In-ecliptic | −3 ± 2 | −5.58 ± 0.52 | 57 | 43 | – | – |
| (b) Latitude < 30° | +1 ± 2 | −2.78 ± 0.61 | 55 | 45 | – | – |
| *Inward (southern hemisphere) fields* | | | | | | |
| (a) In-ecliptic | −5 ± 2 | +4.87 ± 0.46 | – | – | 47 | 53 |
| (b) Latitude < 30° | +1 ± 2 | +4.61 ± 0.47 | – | – | 44 | 56 |
| (c) Latitude > 30° (full width) | +1 ± 2 | +13.55 ± 0.57 | – | – | 42 | 58 |
| (d) Latitude > 30° (90° < $\phi_B - \phi_P$ < 270°) | +1 ± 2 | +6.97 ± 0.42 | – | – | 45 | 55 |

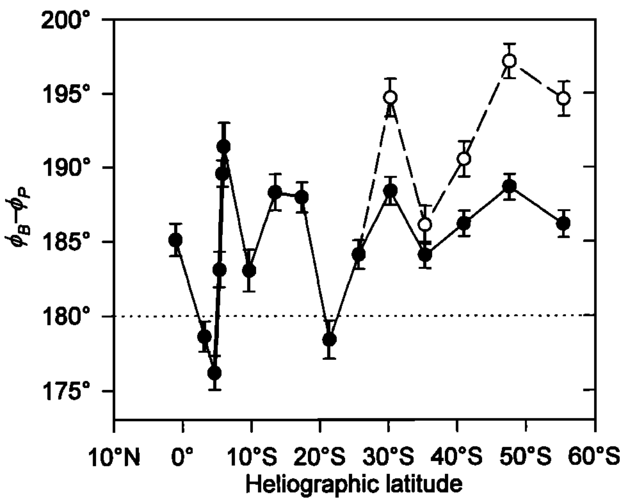


**Figure 6.** Azimuthal angle deviations, $\phi_B-\phi_P$, of the magnetic field direction from that expected from Parker's model, averaged over three solar rotation periods. The error bars represent plus or minus one standard error. The solid line is calculated from azimuthal angles in the range 90° < $\phi_B-\phi_P$ < 270°, while the dashed line is calculated from the full width of the azimuthal angle distribution at latitudes greater than 30°S.

observing field lines less tightly wound than the expected spiral than there is of observing field lines which are more tightly wound. To allow us to make better comparison with cases (a) and (b), Table 1 also lists statistics calculated when the distribution in case (c) is limited to azimuthal angles between 90° and 270°. In this case the mean and the percentages of observations lying either side of 180° are much closer to the corresponding values in cases (a) and (b) indicating that the shapes of the distributions are similar. As corroboration, the standard deviations for the southern hemisphere distributions are 35.4°, 37.5°, and 35.6° (excluding the wings), indicating that the width of the distribution does not vary greatly over the three intervals.

Figure 6 shows the results of our check for any underlying trends with time or position. Each point represents the mean of $\phi_B-\phi_P$ for the southern hemisphere sector calculated over three solar rotation periods and plotted against south heliographic latitude. The error bars provide an indication of the spread of results in each interval and represent plus or minus one standard error. The mean values at higher latitudes connected by a solid line are those calculated ignoring the wings of the distributions (90° < $\phi_B$ < 270°). For comparison, those calculated from the full width of the distribution are connected by a dashed line. This plot serves to confirm the results presented above that there is no significant change in the mean azimuth angle up to a latitude of 60°S when one ignores the large deviations in the wings of the distributions.

It was found to be more difficult to check for trends in the most probable value of $\phi_B-\phi_P$ because of the reduced number of observations in the three solar rotation period distributions. The poorer statistics lead to large error bars of between ±5° and ±10° on the most probable values. In general, for these distributions accumulated over shorter time intervals, it is not possible to state that the most probable values are significantly different from either the expected value of 180° or from the mean values in Figure 6 which ignore the distribution wings. However, if the wings are taken into account at latitudes greater than 30°S, as seen for case (c) above, the most probable values and the mean values are significantly different.

Considering next the meridional angle results shown in Figure 7, again we can see that the most frequently observed angle is within a single 5° bin width of the expected angle. Some statistics for these distributions are presented in Table 2. The histograms in Figures 7a and 7c are roughly symmetric, although by inspection the Figure 7c histogram appears to have a greater number of smaller deviations than the

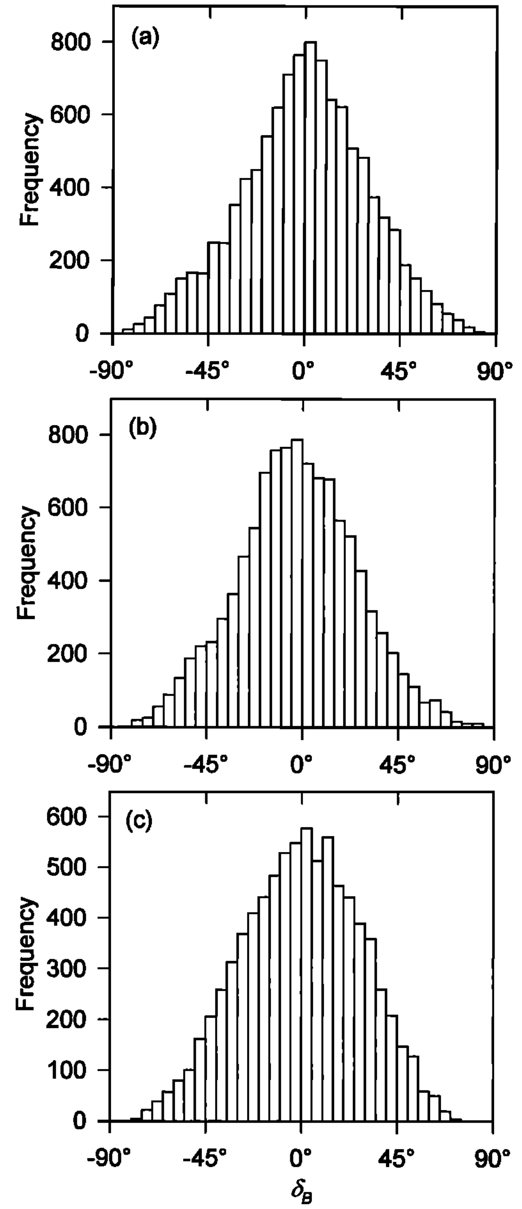


**Figure 7.** Histograms of the deviation in meridional angle, $\delta_B$, from the Parker model magnetic field direction binned into 5° intervals for (a) the in-ecliptic cruise phase of the Ulysses mission, (b) the out-of-ecliptic phase for heliographic latitudes between 6°S and 30°S, and (c) latitudes between 30°S and 60°S.

**Table 2.** Statistics of Meridional Angle Deviations From the Expected Parker Model Direction

| Latitude Range | Most Probable Value, deg | Mean ± Standard Error | < 0°, % | > 0°, % |
|---|---|---|---|---|
| (a) In-ecliptic | +2 ± 2 | +0.45 ± 0.29 | 48 | 52 |
| (b) Latitude < 30° | −5 ± 2 | −2.17 ± 0.27 | 54 | 46 |
| (c) Latitude > 30° | +1 ± 2 | +0.10 ± 0.31 | 49 | 51 |

other two (that is, near the peak of the distribution the number of observations in each bin drop off less rapidly with deviation from the peak). Only in the Figure 7b histogram is there a suggestion of an asymmetry where there appears to be a bias toward negative deflections of $\delta_B$. We wished to investigate whether this bias was due to a consistent asymmetry throughout the period over which the histogram was accumulated or whether it was alternatively due to variation of the position of the peak of the distribution being "smeared out" because of the long accumulation period. With this aim we calculated distributions of $\delta_B$ over three solar rotation period time intervals as described in the previous section.

Figure 8 shows the results plotted against heliographic latitude in a similar manner to Figure 6. The region where we found consistently negative deviations of $\delta_B$ is fairly obvious, lying between 6°S and 30°S; this is the data interval over which the Figure 7b histogram was accumulated. It is also apparent from this plot that during the early part of the "in-ecliptic" cruise when Ulysses spent a brief period at positive heliographic latitudes there is a tendency for the meridional angle to have a positive deflection with respect to the *RT* plane. By inspection of this plot it appears that in a region within about 25° of the heliographic equator there is a trend north of the equator toward increasing positive deflections of $\delta_B$ with latitude and a trend south of the equator toward increasing negative deflections with increasing southerly latitude. The effect is strongest with a deflection of the order of 4° between about 15°S and 20°S. Looking at increasingly

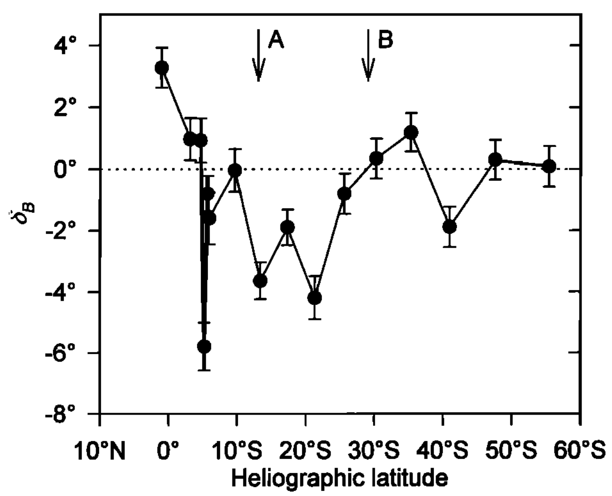


**Figure 8.** Meridional angle deviations, $\delta_B$, of the magnetic field direction from that expected from Parker's model. The error bars represent plus or minus one standard error. The arrows labelled "A" and "B" represent points at which significant changes took place in the solar wind flow pattern (see discussion in text).

south latitudes beyond about 25° the elevation angle appears on average to conform to what is expected.

As our analysis of the azimuthal angle has taught us that asymmetries can lead to the mean value being different from the most probable value of a distribution we also checked the behavior of the most probable value of $\delta_B$ for each of the shorter duration intervals. As in the case of the azimuthal angle, large error bars resulted because of the poorer statistics. A similar trend, although less clearly defined than that of the mean value of $\delta_B$, was found. No clear evidence was found for any systematic difference between the mean and most probable values.

## Discussion

The passage of Ulysses at 30°S to regions above the maximum latitudinal extent of the heliospheric current sheet [*Smith et al.*, 1993] and further, into a region dominated by the solar wind flow from the southern polar coronal hole [*Phillips et al.*, 1994], has allowed us to study the distributions of the deviations of the azimuthal and meridional angles of the magnetic field from the expected Parker spiral model direction, avoiding possible confusion generated by the presence of the sector structure.

### Azimuthal Angle

In the magnetic fields originating in the south polar coronal hole the distribution of the azimuthal angle deviation, $\phi_B - \phi_P$, is found to be highly asymmetric, with a most probable value in agreement with the Parker model, but with a greater probability of observing field lines with $\phi_B - \phi_P$ greater than 180°, that is, less tightly wound than the Parker prediction. Evidence has been presented that the shape of the distribution is, however, not very different from that observed at lower latitudes and that the extent of the asymmetry at lower latitudes may be masked due to the distributions arising from the northern and southern hemisphere sectors overlapping. Study of the near-ecliptic data has suggested that the direction of this asymmetry is reversed to the north of the heliospheric current sheet.

From a statistical point of view the near-ecliptic portion of our results are consistent with previous studies reporting that the included azimuth angle between the inward and outward sector magnetic field directions is less than 180° [*Svalgaard and Wilcox*, 1974; *King*, 1976], interpreted as being due to a north-south asymmetry in the heliospheric magnetic field direction. (Note that the word "asymmetry" is being used here to describe the difference in winding angle north and south of the current sheet rather than the asymmetry of the azimuth angle distributions discussed above.) A number of more recent studies have looked at this in greater detail [*Bieber*, 1988; *Smith and Bieber*, 1993; *Sabbah*, 1994]. *Smith and Bieber* [1993] analyzed a large data set from a number of spacecraft at 0.7 and 1.0 AU and reported an average difference of 2.4° ± 0.9° between the mean field azimuth angles to the north of the heliospheric current sheet when compared to the south of the current sheet, that is, the northern hemisphere mean field was more tightly wound than the southern hemisphere mean field. Their study clearly showed that this was a north-south asymmetry rather than an asymmetry between outward pointing magnetic field sectors and inward pointing sectors, as the northern hemisphere azimuth angles remained more tightly wound through the 11-year solar magnetic field reversals. Our in-ecliptic results from Ulysses also show that typically the mean field azimuth angle, when compared to the expected spiral angle, is biased toward more tightly wound angles north of the current sheet and to less tightly wound angles south of the current sheet. Although our data set is not extensive enough on its own to retest the north-south versus outward sector-inward sector question, it is clear that our results do not contradict the picture presented by *Smith and Bieber* [1993].

When Ulysses is far enough south of the current sheet to be sampling purely southern hemisphere fields we can see the full extent of the asymmetry in the distribution of field azimuth angles biased strongly in a "less tightly wound" sense. Here the mean field azimuth angle moves well away from the expected spiral direction by about 13°, while the most probable azimuth angle remains close to that expected. The observation that the shape of the distribution is similar to that at lower latitudes raises the question of whether it is the number of observations in the extreme wings of the distributions that is leading to the departure of the mean field azimuth angle from the expected spiral direction and hence the north-south asymmetry in the mean azimuth angle described by *Smith and Bieber* [1993]. If this were to be the case, then a further consequence of the similarity of the high- and low-latitude distributions for inward sectors, is that the same similarity should apply to outward sectors. Thus, when Ulysses recently passed to the north of the heliospheric current sheet during 1995, we might expect to observe a field azimuth angle distribution strongly biased from the expected spiral angle in a "more tightly wound" sense as opposed to the "less tightly wound" sense currently observed in the south. However, data obtained while this paper was under review has shown that this is in fact not the case and that the equivalent northern hemisphere distribution to Figure 5c is also biased in a "less tightly wound" sense. The implication of this observation is that the asymmetries in our near-ecliptic distributions and the north-south asymmetry of *Smith and Bieber* [1993] are due to different phenomena than the asymmetric distributions we found in the higher-latitude unipolar fields.

So far the discussion has concentrated on the statistical aspects of our results, but we should consider physically how the asymmetries in the azimuth angle distributions might arise. Because the measured radial component of the solar wind velocity has been included in our calculation of the expected spiral angle, and it is the local (to Ulysses) solar wind velocity that is relevant in determining the spiral angle, it cannot be radial component velocity variations of the type considered in Parker's model that are leading to the spread in our azimuth angle distributions. This point is illustrated in Figure 9, where we show a histogram for the 30°S-60°S region of the measured hourly $\phi_B$ values rather than $\phi_B-\phi_P$ as in our earlier figures. Superimposed in grey is the distribution of $\phi_B$

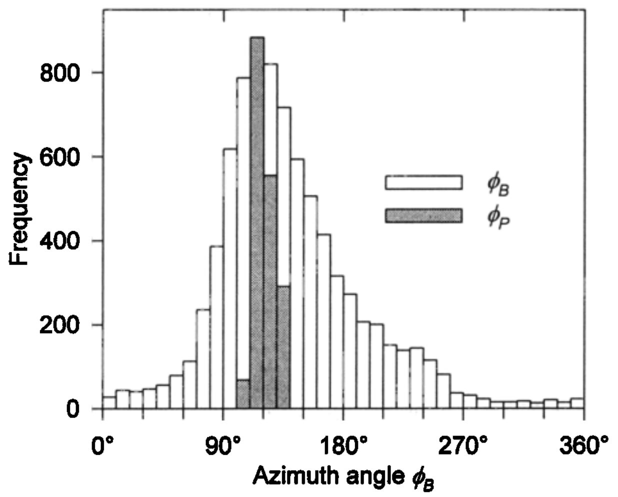


**Figure 9.** A histogram of the azimuth angle $\phi_B$ accumulated at latitudes between 30°S and 60°S. Superimposed in grey is the distribution which would be obtained if all our observations agreed with the calculated value of $\phi_P$, normalized to have the same maximum value.

(rescaled to have the same maximum value) which would result if every observation agreed with the Parker model $\phi_P$ azimuth angles we have calculated from (3) using the heliographic position of Ulysses and the measured solar wind velocity. The spread in this distribution thus arises only from the slowly changing position of the spacecraft and the measured velocity fluctuations (note that the distribution of $\phi_P$ itself is asymmetric as a result). Transforming back to our usual $\phi_B-\phi_P$ distributions would give a single bin centered on 180° if all our observations agreed with our calculated $\phi_P$. The majority of the $\phi_B$ which lie far from $\phi_P$ must thus be generated by some other mechanism. To emphasise this point, considering (3), it is possible to calculate that a radial component of solar wind velocity in excess of 1000 km/s would be required to produce an azimuth angle at the mean deviation (13° less tightly wound than expected) in the 30°S-60°S distribution. This is clearly inconsistent with the observed solar wind velocity, even if fluctuations within a single hourly average are taken into account.

A further potential source of our deviations could be the azimuthal velocity component $v_\phi$ also a term in (3) but ignored in our calculation of the expected spiral angle. It is worth noting that a systematic $v_\phi$ in the anticorotation direction both north and south of the heliospheric current sheet could produce the $B_\phi$ deviations of the north-south asymmetry in near-ecliptic data. However, again, it is possible to calculate that, for example, a $v_\phi$ of the order of 400 km/s opposed to the solar rotation direction would be required to produce a 13° underwound field azimuth angle. The typical $v_\phi$ observed at Ulysses is of the order of 20 km/s, so it is not possible that the majority of the larger deviations that we observe are due to variations in the azimuthal component of the solar wind velocity. Equation (3) is derived from the requirement that there be zero electric field in the frame of reference corotating with the Sun. This also means that it is not possible to have a systematic $B_\phi$ deviation from the Parker model in the absence of a $v_\phi$ component.

A feature of the behavior of the heliospheric magnetic fields originating from the south polar coronal hole which has become very apparent in the Ulysses data is the presence of large-amplitude low-frequency (periods of the order of hours) Alfvén waves [*Smith et al.*, 1995]. There can be little doubt that it is the magnetic field fluctuations associated with these waves that are leading to the majority of the deviations in our 30°S-60°S distribution of the magnetic field azimuth angle. We suggest that these waves can also produce the asymmetries in the distributions. While we are unable at present to give a complete physical story of why the distributions have the shape they do, we can present some arguments to show that our hypothesis is reasonable. Noting that the transverse amplitudes of the waves $\delta B$ are large enough to have $\delta B/B \approx 1$, it is clear that the waves will cause angular deflections of the order of $\tan^{-1}(\delta B/B) \approx 45°$ in our observed values of $\phi_B$, which is compatible with the deflections we observe. *Smith et al.* [1995] have also shown with the aid of a minimum variance analysis that these Alfvén waves are propagating outward close to the radial direction rather than along the mean field direction. Assuming a symmetrical distribution of transverse Alfvénic perturbations perpendicular to the radial propagation direction, if one superimposes this distribution onto a mean Parker model field at, say, 50° to the radial direction, applying (1) suggests that an asymmetric distribution of fluctuations will be obtained around the model field direction simply due to the nonlinear behavior of the tangent function. This simplistic picture does imply that the larger deviations will be in the "less tightly wound" sense in both the southern and northern hemisphere magnetic fields, in agreement with what we are observing in the unipolar fields originating in the polar coronal holes. A more thorough analysis of angular deflections produced by the Alfvén waves is required to pursue this topic further.

### Meridional Angle

Considering now the distributions we have obtained for the meridional angle, again it seems reasonable that the majority of the larger deviations of $\delta_B$ away from 0° are due to the presence of the large-amplitude waves. That the distributions remain generally symmetric about the mean throughout the period studied is consistent with our comments above regarding the fluctuations being transverse to the radial direction. The reason for the apparent asymmetry in the Figure 7b 6°S to 30°S distribution was found in the previous section not to be due to a consistent asymmetry throughout the interval; rather, from the analysis of distributions accumulated over shorter intervals, it was found to be due to a slow variation with either time or position of the peak angle of the distribution as measured by both the mean and most probable angles. When the mean deviation is plotted against latitude (Figure 8), evidence is found of a tendency for negative deflections of $\delta_B$ south of the heliographic equator at latitudes up to about 25°S and weaker evidence for positive deflections during the short period when Ulysses was north of the equator early in the mission. From Figure 8 it would appear that we are seeing the greatest negative deflection to be about 4° between approximately 15°S and 20°S.

Since field lines south of the heliospheric current sheet are presently directed inward toward the Sun, as shown in Figure 4, a negative deflection of $\delta_B$ is indicative of a field line which is being deflected toward the equator with increasing distance from the Sun. However, for much of time when we see consistent negative deflections, Ulysses was still sampling magnetic fields from both inward and outward sectors. However, a negative $\delta_B$ in outwardly directed field lines is also consistent with an equatorward deflection. Additionally in both inward and outward polarity fields a positive $\delta_B$ is indicative of a poleward deflection of field lines. Thus the on-average negative deflection of $\delta_B$ that we saw with Ulysses south of the heliographic equator is consistent with on-average equatorward deflections of field lines at the location of the spacecraft. Although the observation of consistently positive deflections of $\delta_B$ north of the heliographic equator is weaker because of the smaller number of three solar rotation averages covering that portion of the data set, the observation is consistent with an on-average poleward deflection of field lines in this region. The question is then raised of whether the poleward deflection that we see north of the heliographic equator and the equatorward deflection when Ulysses is south of the equator are due to the corresponding polarity sector dominating the interval covered by the appropriate three-solar-rotation period average. This was checked by separating out $\delta_B$ values obtained in the opposing sectors (identified by testing for $\phi_B - \phi_P$ within ±90° of either 0° or 180°) and was found not to be the case; that is, the same approximate trend in the mean $\delta_B$ was found in both polarity sectors.

A possible cause of our nonzero averages of $\delta_B$ could be that they are produced by transient events such as CMEs. As stated earlier, we did carry out an analysis in which we removed CME-affected intervals from the data; rather than removing the trend in the deflections of $\delta_B$ it simply increased the error bars around the averaged data points. The single large data point of $\delta_B = -6°$ does appear to be CME-related, although it was diminished but not totally eliminated by removing the CME interval from the data. Thus, although CMEs may be having a partial influence on our results, they are certainly not the dominating factor.

The remaining, most likely cause of the deflections we observe in $\delta_B$ is that they are related to north-south deflections in the solar wind velocity in the vicinity of corotating interaction regions (CIRs). In Figure 8 the arrow labelled "A" represents the latitude (about 13°S) at which Ulysses started to spend part of each solar rotation in a high-speed velocity stream originating from the northward extension of the southern polar coronal hole [*Bame et al.*, 1993]. The arrow labelled "B" represents the latitude (about 29°S) at which the lowest-speed solar wind originating from around the heliomagnetic equator was no longer sampled. Between these two latitudes the modulation of the magnetic field by the CIRs generated by the interaction between these two solar wind streams was greatest. Thus the fact that we see the greatest on-average deflections of $\delta_B$ in the same region is suggestive of the role of the CIRs in their generation.

A recent study of similar effects using higher time resolution data from Ulysses than used here has been carried out by N. Murphy et al. (Correlated variations in the azimuthal and elevation angles of the heliospheric magnetic field, submitted to *Proceedings of Solar Wind 8*, 1995), who found magnetic field deflections that were consistent with the model of *Pizzo* [1991]. Figures showing examples of meridional solar wind flow deflections associated with CIRs can be found in work by *Gosling et al.* [1993, 1995]. Equatorward deflections of flow are found in the fast solar wind downstream of CIR forward shocks and poleward deflections of flow in the slow solar wind downstream of CIR reverse shocks. Hence it is possible that the small average meridional field deflections we have found in this study are a result of averaging over short intervals of both directions of deflection associated with such solar wind flow deflections. A more detailed study combining work similar to that of Murphy et al., referred to above, with solar wind velocity measurements should help to confirm these possibilities.

## Conclusions

Our analysis of the average magnetic field direction over the trajectory of the Ulysses spacecraft during, first, its in-ecliptic cruise and, second, its early out-of-ecliptic mission phase to latitudes of 60°S, when compared to the simple predictions of the Parker spiral model, has yielded the following results:

1. In general, within 60° of the heliographic equator, the most probable magnetic field direction as measured by Ulysses is close to that predicted by the Parker spiral model.

2. As Ulysses has travelled to higher southern latitudes up to 60°S, into the region dominated by the southern polar coronal hole, the distributions in azimuth angles of the spiralling magnetic field lines are revealed to be highly asymmetric, with field lines which are "less tightly wound" than the most probable and also the expected spiral angle being more common than those which are "more tightly wound."

3. At south heliographic latitudes within 25°S there is evidence that the magnetic field lines are on average directed slightly equatorward of their expected direction, most likely due to solar wind flow deflections associated with corotating interaction regions.

Much of the conclusions presented above will be put to the test as Ulysses continues in its polar orbit round the Sun. In particular, the south polar data have recently been analysed *by Forsyth et al.* [1995]. The second orbit of Ulysses around the Sun will provide a long slow meridional scan, including northern and southern latitudes, of about 3 years at 5 AU through the region where we are seeing the meridional angle deflections of result 3 and should thus provide a good opportunity for further more detailed study of that phenomenon.

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A. Balogh and R. J. Forsyth, Space and Atmospheric Physics, The Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom. (e-mail: a.balogh@ic.ac.uk; r.forsyth@ic.ac.uk)

G. Erdös, KFKI Research Institute for Nuclear and Particle Physics, PO Box 149, Budapest 114, H-1525, Hungary. (e-mail: erdos@rmk530.rmki.kfki.hu)

D. J. McComas, MS D466, Los Alamos National Laboratory, Los Alamos, NM 87545. (e-mail: dmccomas@lanl.gov)

E. J. Smith, MS 169-506, Jet Propulsion Laboratory, Pasadena, CA 91109-8099. (e-mail: esmith@jplsp.jpl.nasa.gov)

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