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Ulysses observations of the radial magnetic field

Edward J. Smith
Jet Propulsion Laboratory, California Institute of Technology, Pasadena,

A. Balogh
Blackett Laboratory, Imperial College, London, United Kingdom

Abstract. The radial component of the magnetic field in the southern hemisphere has been measured at Ulysses as it traveled from the equator to -80.2° latitude and returned. The radial component multiplied by the square of the radial distance, i.e., $B_R r^2$, averaged over 77 day intervals (three solar rotations) is approximately constant at -3.5 nT and shows no evidence of a dependence on heliographic latitude. To discriminate against possible time variations, the measurements have been compared with simultaneous observations in the ecliptic by IMP-8. The two sets of observations agree very well confirming the absence of a significant latitude gradient. Since the sun's dipolar magnetic field component is strong at this phase of the sunspot cycle, it is inferred that magnetic flux from the polar cap is transported to lower latitudes in the solar wind source region to produce a uniform radial field. Such a configuration would be expected if magnetic stresses are influencing the solar wind flow near the sun and are contributing to a non-radial deflection. Estimates of the flux of open field lines (3×10^{14} webers), of the non-radial solar wind expansion (~3) and the polar cap magnetic field strength (~5 Gauss) are derived.

Introduction

Previous attempts to investigate the gradient of the magnetic field have been severely restricted in latitude. Luhmann et al. (1988) compared B_R values at Pioneer 12 (Pioneer Venus Orbiter) and ISEE-3 when the spacecraft were separated by ≈ 0.3 AU and by latitude differences ranging up to 14°. A periodic dependence on heliographic latitude was found characterized by a north-south asymmetry, the field being stronger in the northern hemisphere. Voyager 1,2 data at large distances in association with simultaneous IMP-8 measurements at 1AU were used by Burlaga and Ness (1987) to study the latitude gradient in field magnitude, B, between the equator and 30° north. It was concluded that, at this specific time and location, the field was weaker at higher latitude.

The limited observational opportunities have been supplemented by theoretical models of the solar field and its extension into the heliosphere. For example, Pneuman and Kopp (1971) explored the effect of stresses exerted by the magnetic field and solar wind on a magnetic dipole. Other models are based on extrapolation of observed photospheric fields to a source surface at several solar radii where the field is carried off by the radial solar wind (Hoeksema, 1992). Implicit in the models are various latitude dependences.

Knowledge of the magnetic field gradient has important implications for the solar wind. In the hydrodynamic model developed originally by Parker (1953), the field played a completely passive role. However, subsequent models have shown that the magnetic field can have a very significant effect. The magnetic field structure also influences energetic particles of both solar and galactic origin.

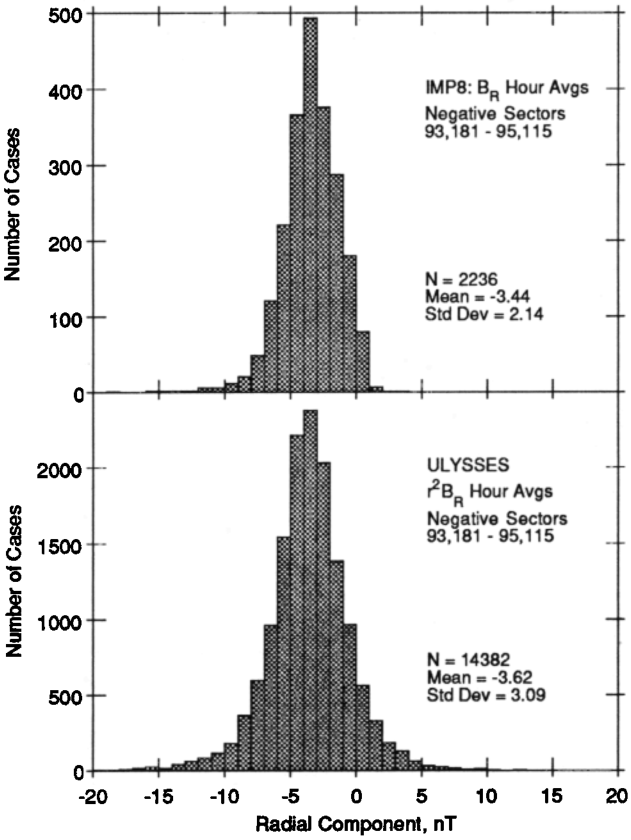

Figure 1. Probability distributions at Ulysses and IMP-8. Histograms of B_R averaged over one hour are shown over the interval from 1993.5 to 1995.3. The radial components at IMP-8 correspond to times when the spacecraft was inside negative magnetic sectors. Since B_R is positive when directed outward from the sun in Solar Heliospheric coordinates, the probable values and averages are negative at both spacecraft. The probability distributions are very similar in spite of the large separation in heliolatitude. The means at Ulysses and IMP are -3.6 and -3.4, respectively.

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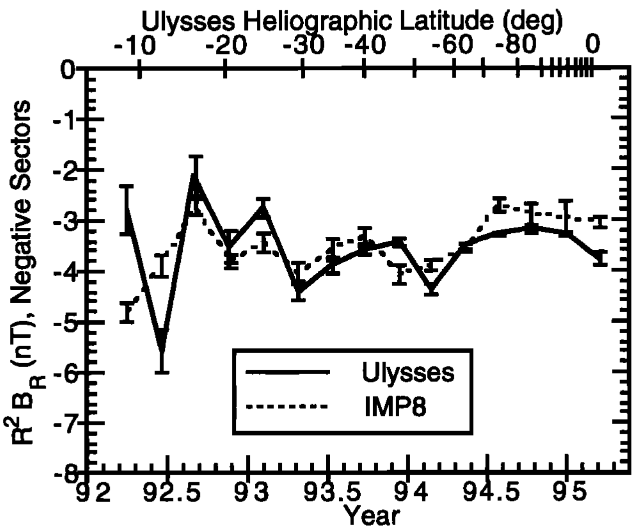

Figure 2. Radial Field components at Ulysses and IMP-8. The solid lines represent 77 day averages of $B_R r^2$ at Ulysses over the interval from 1992 to 1995. The heliographic latitude of the spacecraft shown along the upper scale indicates the descent from -30° to 80.2° and the rapid return to the equatorial region. The IMP-8 measurements (dashed lines) are for the same time intervals but are restricted to measurements made in negative sectors. The vertical lines represent the standard errors associated with each average. The close correspondence between the two sets of measurements is striking. There is no evidence of a significant latitude gradient at any time or latitude separation. The absence of a secular time variation over the 3 year period is attributable to the observations being made near sunspot minimum.

Observations of the radial component, B_R, are presented here. They represent the first comprehensive survey of the latitude gradient and include observations at previously inaccessible latitudes above 30°. Preliminary Ulysses results on the latitude gradient have been reported previously (Smith et al., 1995; Balogh et al., 1995).

Observations

The radial field component, B_R, is a characteristic property of the solar magnetic field. The azimuthal field component, B_T, is a direct consequence of B_R and is dependent on the solar wind speed and the angular rotation of the open field lines in the corona. Furthermore, B_T is strongly affected by the large amplitude Alfvén waves that have been found to be continuously present above ~50° latitude (Smith et al., 1995). Since the waves propagate radially, their effect on B_R is significantly smaller.

B_R is easily corrected for the radial gradient, a necessity because the spacecraft trajectory involves correlated changes in latitude and distance. The Ulysses measurements have been extrapolated back to 1AU by calculating $B_R r^2$ along the orbit.

A potential disadvantage in using B_R is the high degree of accuracy required at large radial distances. B_{Ro} = 3.5 nT at 1AU implies B_R = 0.14 nT at 5AU. However, the Ulysses Vector Helium Magnetometer has provided exceptional accuracy at the level of a few picoTesla so that B_R is readily measured. The magnetic field investigation is described in Balogh et al. (1992).

To cope with possible time variations, in-ecliptic baseline measurements are needed. Fortunately, magnetic field measurements are available from IMP-8 (courtesy of R.P. Lepping). The large circular orbit with $r \approx 30 r_E$ lies outside the Earth's bowshock on the front side and is in the solar wind for ~ 7 out of ~ 12 days. The solar wind measurements were identified by inspection of one minute averages of the vector field and when necessary by comparing with plasma velocities.

Analysis and Results

The strategy was adopted of analyzing magnetic measurements after Ulysses left the low-latitude fan-shaped region in which the heliospheric current sheet, stream-stream interactions and CIRs were dominant. Ulysses passed above the HCS at approximately -30° latitude (Smith et al., 1993). From then on, only negative polarities characteristic of the south hemisphere at this phase of the solar cycle were observed. Ulysses measurements of $B_R r^2$ were averaged over successive time intervals of 77 days (3 solar rotations). .

In principle, B_R may also be dependent on longitude even in the free-streaming solar wind at high latitude. Averaging over several solar rotations has the effect of suppressing a longitude dependence which we examine subsequently.

To compare like fields, we restricted the measurements at IMP-8 to intervals of inward-directed (negative) fields. We averaged these measurements over the same time intervals as at Ulysses. Time variations continue to be of concern, however, especially interaction regions at IMP and Alfvén waves at Ulysses. To test for the self-similarity of the two data sets, histograms of B_R at Ulysses and IMP-8 were compared (figure 1). The two distributions compared very well, lending confidence to the use of average values at the two locations as the appropriate measure.

The average values of B_R so obtained are shown in figure 2. Ulysses measurements of $B_R r^2$ are connected by solid lines and the IMP-8 measurements by dashed lines. The data are plotted as a function of time with latitude given along the top scale. Large numbers of measurements are included in the averages. The vertical bars are the customary standard "errors", actually the statistical uncertainty, in the averages. The uncertainties are not instrumental but are caused by time variations at both locations. This figure is an extension over the full latitude range of the results reported previously up to -50°.

The obvious features in figure 2 are the apparent absences of both a long-term time variation and a significant latitude gradient. The shorter period time variations are generally well-correlated at the two spacecraft in spite of their large separation in distance and latitude. The largest differences occur in early 1992 when the variations in B_R are also largest, presumably the effect of solar activity. Both data series can be fit by an overall average of ≈ -3.5nT, a value that is typical of B_R at 1AU at this phase of the solar cycle. In view of the statistical uncertainties, a small gradient of perhaps 0.01nT deg^{-1} corresponding to a maximum change of 0.8 nT from equator to pole cannot be excluded.

Absence of a significant latitude gradient, which is contrary to many models of the solar heliospheric field, was examined further by plotting $B_R r^2$ at Ulysses at higher time resolution and as a function of Carrington solar longitude (figure 3). An inclined rotating solar dipole could result in a periodic variation in B_R. Considerable structure of a random nature is present. Nevertheless, no significant variation in B_R attributable to the field of a rotating dipole or other longitude dependence is evident. This result supports the apparent absence of a latitude gradient inferred from figure 2.

Absence of a longitude dependence has significant implications for the charged particle measurements being made simultaneously at Ulysses. The energetic particles locally accelerated by CIR shocks and the galactic cosmic rays continue to show periodicities at high latitudes (Simpson et al., 1995). At low latitude, the energetic particle variations accompany increases in field strength. However, at high latitude, where $B \approx B_R$, no such increases are evident. The acceleration and modulation must be non-local.

Discussion

Absence of a latitude gradient has significant implications for the solar wind and models of the solar-heliospheric field. A strong dipole component of the photospheric-coronal magnetic field during the declining phase and minimum in solar activity is well-established by the accumulated observations of solar magnetographs.

Given the strong polar field near the sun, the Ulysses observations imply that such fields are being transported equatorward to produce a uniform B_R somewhere between the sun and 1AU, presumably in the solar wind source region. The solar wind must also be diverging from higher to lower latitudes as it accelerates outward. Attempts to extrapolate observed solar wind properties back to the source region cannot rely on extrapolation based simply on radial flow.

Evidence of such a divergence has been available in x-ray and white light coronograph images which outline plume-like diverging polar magnetic fields and imply a latitude gradient in the solar wind density (Munro and Jackson, 1977). Models have been developed in which divergence is included driven by higher pressure over the pole than near the equator. In terms of magnetic pressure, $B^2/8\pi$, there will be a magnetic force directed from the pole toward the equator. An alternative view is that the latitude-dependence of B_R implies an azimuthal current, j_ϕ. The magnetic stress, $j_\phi B_\theta$, will be equatorward.

In general, a gradient in the solar wind pressure will also contribute to the divergence. A model developed by Suess et al. (1977) includes both the plasma and magnetic pressures and leads to a uniform magnetic field by the time the solar wind reaches 5 solar radii. However, the model leads to the opposite divergence, poleward and away from the equator, at greater distances.

The absence of a significant latitude gradient is unlikely to be a coincidence. A uniform field distribution suggests that the magnetic stresses have been relaxed and are no longer effective. Magnetic stresses may be dominating the solar wind divergence in the source region.

The Ulysses results raise serious questions about the potential field models. They involve extrapolation of measured photospheric magnetic fields to a surface (or surfaces) at which a boundary condition is applied such as the elimination of non-radial fields (e.g., Hoeksema et al. 1983). Extrapolation is based on a spherical harmonic representation of the field and currents are often assumed to be absent between the photosphere and the source surface, a dubious assumption in view of the Ulysses observations.

Attempts have been made recently to improve the agreement with the observations by including the field of the HCS (Wang, 1993; Zhao and Hoeksema, 1995). The current sheet produces a B_R that is uniform. (To avoid confusing cause and effect, it is correct to say that a uniform B_R which reverses sign at the equator gives rise to the sheet current.) However,

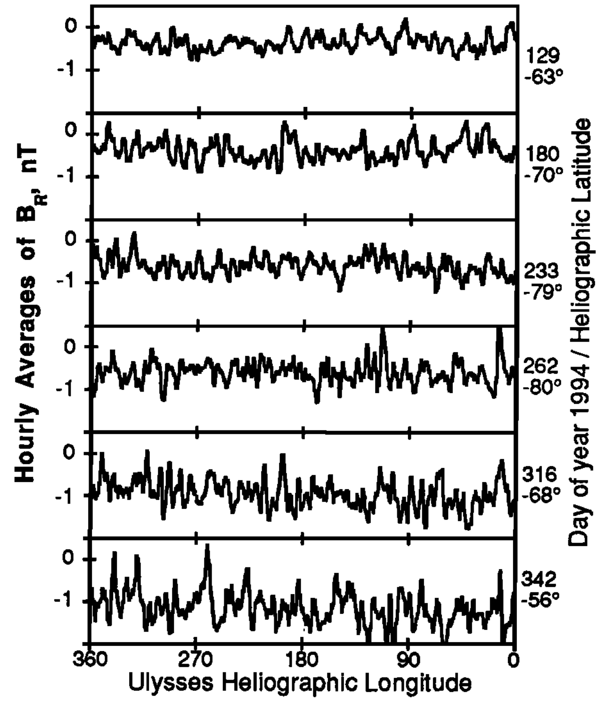

Figure 3. B_R at Ulysses as a function of Carrington Longitude. Hourly averages of B_R are displayed for 6 solar rotations centered on maximum heliographic latitude. The time intervals and latitude at a longitude of 180° are shown at the right of each panel. The Carrington longitudes correspond to the subsolar location of the spacecraft. Random short period variations are Alfvén waves continuously present above ≈ 45°. No long period sinusoidal variation indicative of a dependence of B_R on longitude is evident.

the effect of the dipole-like photospheric fields typically leads to a latitude gradient with stronger fields at higher latitudes.

The Ulysses observations yield an accurate measure of the flux of open magnetic fields in the south hemisphere. The constant $B_R r^2$ implies $\Phi = 2\pi B_R r^2 \approx 3 \times 10^{14}$ webers. If B_R is uniform, the statistical uncertainty is ≈1%. If a pole-to-equator difference of 1nT is assumed, an uncertainty of several tens of percent is possible.

This result is useful in providing an estimate of the solar wind expansion (or spreading) factor, which quantifies the flow divergence. In principle, this factor can be obtained from surface area and magnetic field strength, i.e., the magnetic flux, of the south polar coronal hole. The expansion factor is the ratio of the two spherical areas or solid angles occupied by this flux near the sun and as measured by Ulysses.

Simple models of the polar magnetic field can be used to estimate the divergence and the polar cap field strength. The following illustrative calculation will assume azimuthal symmetry so that the solid angles associated with the polar coronal hole, Ω_P, and the fast solar wind, Ω_F, are given by the co-latitude of their equator-most edge. We assume that the fast wind occupies the region above 45° latitude in agreement with the appearance of a continuous speed of ≈750km/sec. The corresponding solid angle above 45° is then $\Omega_F = 2\pi\,(1-\cos(\pi/4)) \approx 0.6\pi$ ster. The magnetic flux within this solid angle is $\Phi_F = r_0^2\, B_{Ro}\, \Omega_F \approx 0.6\pi r_0^2\, B_{Ro}$.

We represent the radial field by $B_R = B_P \cos^n(\theta)$ where B_P is the field strength at the pole at distance, r_s, taken to be a solar radius. The index, n, will be allowed to range from n = 0, a uniform field within the coronal hole, to n = 8, a value proposed by Svalgaard et al. (1978) based on photospheric field observations which presumably represents extreme concentration of magnetic flux near the pole. The case, n = 1, corresponds to a dipole field.

The magnetic flux passing outward through the polar cap is given by

$$\Phi_P = 2\pi B_P r_S^2 \int_0^{\theta_P} \cos^n(\theta) \sin\theta \, d\theta.$$

$$= 2\pi B_P r_S^2 (1-\cos^{n+1}(\theta_P))/(n+1).$$

This flux occupies a solid angle, $\Omega_P = 2\pi\,(1-\cos\theta_P)$. Equating the two fluxes, $\Phi_F = \Phi_P$, implies that

$$\cos^{n+1}(\theta_P) = 1 - (n+1)\,(r_O/r_S)^2\,(B_R/B_P)\,(\Omega_F/2\pi).$$

For assumed values of B_P and n, θ_P can be calculated and used to obtain Ω_F. The expansion factor, $S = \Omega_F/\Omega_P$, is plotted in figure 4 for various combinations of B_P and n.

For a uniform field (n = 0) with B_P = 2 Gauss, S = 2. However, S is significantly larger for stronger fields. Thus, B_P = 5G implies S = 3 while 10G implies S = 6. Furthermore, S is weakly dependent on n. For reasonable field strengths exceeding a few Gauss at the pole, a large expansion of 3 or more is implied.

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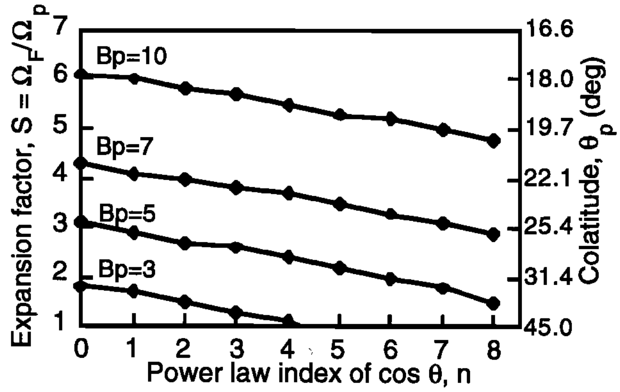

Figure 4. Solar wind expansion factor deduced from the magnetic flux observed in the polar cap. The expansion (spreading) factor, S, is the ratio of two solid angles. One (Ω_F) is that occupied by the fast solar wind corresponding to colatitudes above 45°. The other (Ω_P) is the solid angle of the sun's polar cap that would produce the same magnetic flux as observed by Ulysses inside Ω_F. The magnetic flux issuing from the polar cap depends on two parameters, the field strength at the pole (B_P in Gauss) and the index (n) which describes the distributions of flux with latitude. θ_P is the colatitude (shown on the right hand scale). For a dipole field of 5 Gauss, $S = \Omega_F/\Omega_P \approx 3$ corresponding to colatitudes of 45° and 25°.

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E. J. Smith, Jet Propulsion Laboratory, California Institute of Technology, M/S 169-506, 4800 Oak Grove Drive, Pasadena, CA 91109-8099 (e-mail esmith@jplsp.jpl.nasa.gov)

A. Balogh, Imperial College of Science & Technology, The Blackett Laboratory, Prince Consort Road, London SW7 2BZ United Kingdom.

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