Heliomagnetic Latitude Dependence of the Heliospheric Magnetic Field

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Abstract

ICE and IMP-8 magnetic field data from 1984-1988 have been analyzed in a magnetic coordinate system defined by the orientation of the solar magnetic dipole. The heliomagnetic latitude dependence of the radial component of the magnetic field (Br) has then been investigated in the range of magnetic latitudes (rem 60° shove and below the heliospheric current sheet (HCS). Br reverses sign abruptly across the current sheet, consistent with the solar magnetic field models of Pneuman and Kopp [1971] and Wolfson [1985] but inconsistent with the source surface models [Hoeksema, 1986]. No evidence is found for an asymmetry in the magnetic field suggested by earlier studies of interplanetary magnetic field data [Luhmann, 1987, Burton, 1990]. A slight (~.03 nT per degree) latitude gradient has been found which is consistent with the MHD model of Pneuman and Kopp and the recent model of Zhao and Hoeksema [1994].

Introduction

Various approaches have been taken to globally map the observed photospheric magnetic field into the corona. When extrapolated into interplanetary space, these models can be compared with observations. Each model predicts how the magnetic field will vary with latitude and the nature of the field rotation across the HCS or sector boundary. Source surface models which require that at some distance from the Sun the field becomes entirely radial are most widely used and have been successful at predicting the heliospheric current sheet location [Hoeksema et al., 1982] and orientation [Burton et al., 1994]. At distances above the source surface these models do not accurately predict the field magnitude nor do they predict the rapid field reversal seen at sector boundaries. More recent modifications to these models, including the effect of the heliospheric current sheet, have been made in light of the incoming Ulysses high-latitude observations [cf., Zhao and Hoeksema, 1995]. Wolfson [1985] developed a coronal magnetic field model with volume and sheet currents through a purely static solution to the MHD equations. The model predicts a constant field magnitude with latitude, abruptly reversing sign at the heliospheric current sheet. These solutions can be compared to the classic work of Pneuman and Kopp [1971] who solved the steady-state MHD problem iteratively to obtain a self-consistent solution in which magnetic force, gas pressure, gravity and solar wind acceleration everywhere satisfy the momentum equation. The solution results in volume currents throughout the corona as well as current sheets separating oppositely directed field lines. This model predicts an abrupt reversal in the sign of Br at the current sheet, a slight positive gradient with latitude near the equator asymptoticlly approaching a constant value over the poles. The relative variation in radial magnetic field at large distances for these three models is shown schematiclly in figure 1 from Wolfson [1985]. The models mentioned here are by no means an exhaustive list.

Comparisons between Ulysses at heliographic latitudes from 30° to 81° south and IMP-8 near the ecliptic plane show little, if any, evidence of a latitude gradient in long-term (3 solar rotation) averages of the radial component of the field [Smith, 1995]. The absence of a strong latitude gradient implies the dominance of the field by the heliospheric current sheet. That comparison was made when Ulysses reached latitudes beyond that occupied by the current sheet and exclusively negative magnetic field polarity was observed. Ulysses observations were compared with data from negative sectors at IMP-8. Although the gradient at high latitude is small and the field is dominated by the HCS, the question of how the field varies with magnetic latitude near the solar equator was not addressed. In the following, we use in-ecliptic data from ICE and IMP-8 to study this issue in the near-equatorial region.

Previous investigations of the latitude dependence of the interplanetary magnetic field near the ecliptic plane suggested an asymmetry in the strength of the field between the northern and southern hemispheres. In a comparison of Pioneer Venus Orbiter at 0.7 AU and ISEE-3 at 1 AU, Luhmann et al. [1987] found that the magnitude of the radial component of the field was asymmetric and best modeled by a heliolatitude (θ) dependence: $B_r = (1 - .8 \sin\theta)$. Burton et al., [1990] also found that an asymmetric magnetic field yielded the best fit to a comparison of ISEE-3 and IMP-8 observations, both at 1 AU. Neither of these models showed complete agreement with the data.

In this study we have analyzed ICE and IMP-8 data at 1 AU in heliomagnetic coordinates aligned with the solar magnetic dipole, the coordinate system most likely to "organize" the heliospheric magnetic field. As Smith [1995] points out, the radial component of the magnetic field (B_r) merits special attention since it is representative of the magnetic field in the source region of the solar wind. In order to compare with existing solar models we have investigated how B_r varies with magnetic latitude. In particular we will 1) investigate the nature of the magnetic field rotation across the heliospheric current skeet, i.e.., whether the field reverses abruptly or smoothly across the sector boundary, 2) assess any evidence for an asymmetry in the magnetic field between the northern and southern hemispheres, and 3) assess any evidence for a gradient in the field strength with magnetic latitude.

Analysis

The orientation of the solar magnetic equator which defines the coordinate system was determined graphically (rem the source surface neutral line contours of Hoeksema [1 986]. The longitude of the solar dipole is assumed to he 180° from the midpoint of the intcn-sections fo the ascending and descending neutral line contour with zero degrees heliographic latitude. The colatitude of the dipole is simply the pseudoinclination of the neutral line, i.e.., the average of the maximum extent of the neutral line into the southern and northern hemispheres. The neutral line is assumed to be planar and orthogonal to the dipole axis. These simplifications result in a highly idealized version of the neutral line contour varying sinusoidally over a solar rotation. The advantage of this approach is computational simplification, since the magnetic latitude can be determined from only two parameters per solar rotation, the dipole longitude and the pseudoinclination. An example is shown in figure 2 for Barrington rotation 1753 in 1984. The neutral line zero crossings are at 160° and 320° Barrington longitude respectively which implies that the solar dipole is at 60° Barrington longitude. The pseudoinclination (colatitude) for this solar rotation is 413°. The resulting idealized neutral line used to determine the magnetic latitude is shown in panel b.

ICE and IMP-8 data from the minimum and the ascending phase of Solar Cycle 22, 1984-1988 were used for this study. The delay from the source surface to 1 AU was calculated taking into account both the longitude separation of the spacecraft and earth and the transit time from the source surface to 1 AU using the measured solar wind velocity. Since the ISEE-3 velocity measurements are not readily available, a fixed delay was used for that spacecraft. Time series of the radial component of the magnetic field and the magnetic latitude of the spacecraft were inspected. For more than 80% of the examples reversal in the sign of Br occurred within three days of the predicted crossing of zero degree magnetic latitude indicating the method is effective in predicting the location of **sector** boundaries. In addition, solar wind plasma parameters (not shown) measured at IMP-8 show a magnetic latitude dependence similar to previous studies [Zhao and Hundhausen, 1981 and Bruno et al., 1986] i.e., a minimum in velocity and temperature and a maximum in density at zero degrees magnetic latitude. These qualitative agreements give confidence in the method used to determine magnetic latitude.

Hourly averages of Br were binned in five degree heliomagnetic latitude intervals. The signed value of Br was used in ***contrast*** to the earlier study by Luhmann who used the magnitude. Since there is certain amount of error inherent in estimating the sector boundary location, a scheme was used to avoid inclusion of data points from the “wrong” magnetic sector which would artificially lower the bin average by summing positive and negative values of Br from opposite sectors. The polarity of the magnetic field was calculated for each hourly average. Those values with ambiguous polarity (the magnetic field vector lies outside 60° cone angle of the inward or outward Parker spiral direction) were not included in the bin average nor were data points for which the calculated polarity had the ***wrong*** sign.

The results obtained using ICE and IMP-8 data are shown in figure 3 for each of the years 19841-88. The data points represent five degree magnetic latitude bin averages and the error bars are the standard error. The agreement is quite good between ICE (closed circles) and IMP (open circles). Qualitative inspection of this figure reveals several features. 1) An abrupt reversal of the field occurs across the helisopheric current sheet. 2) No evidence for an asymmetric magnetic field is suggested; the field is roughly the same magnitude above and below the current sheet and 3) A small positive gradient in Br with latitude exists.

Discussion and Conclusions

Magnetic coordinates have been found to give a high degree of organization to solar wind plasma parameters in previous studies but no similar study has previously been carried out for the magnetic field. Zhao and Hundhausen [1981] used a tilted magnetic coordinate system to investigate the magnetic latitude dependence of solar wind parameters for six solar rotations in 1974] when the solar wind displayed a simple tilted-dipole configuration. Analytical expressions for the dependence of the various solar wind parameters on magnetic latitude were derived. In another study, using Helios-1, Helios-2 and IMP-8 data from 1976-77, Bruno [1986] investigated the dependence of solar wind parameters on angular distance from the current sheet. The heliospheric current sheet was found to have a strong influence in organizing solar wind parameters. The velocity, density and temperature were found to have a strong latitudinal gradient whereas other parameters including the magnetic energy density were found to have no variation with latitude.

Since the range of heliographic latitudes investigated in this study is small, short-term (hourly) averages have been used. As pointed out by Hundhausen [1978] any evidence of latitudinal variations in solar wind parameters are difficult to observe in solar rotation averages of data unless the spatial variation is simply organized about the solar equator or the range of latitudes covered in the analysis is large. Although the discussion of Hundhausen is applied to the solar wind velocity, it could just, as easily be applied to latitude variations in the magnetic field. As Hundhausen points out, a wide class of possible spatial variations is virtually undetectable in the longitude-averaged parameters observed over a limited near-equatorial latitude range. Although 3-solar-rotation averages at Ulysses show no evidence of a latitude dependence, long-term averages yield no information on the dependence on magnetic latitude since the full range of magnetic latitudes are sampled during a solar rotation. The problem reduces to an investigation of the dependence on heliographic latitude, a distinct problem from what is considered here.

Although none of the solar models predict a linear variation in field strength with latitude, visual inspection of figure 3 suggests it is a reasonable fit to the data for the range of latitudes investigated in this study. The slopes, intercepts and correlation coefficients of a linear fit to the bin averages are shown in Table 1 separately for positive and negative sectors for each year. The average value of Br in positive and negative sectors is also shown. Listed in the last column is the average standard error for each year.

The slopes are consistently positive in both hemispheres at both ICE and IMP-8 for each of the five years of the study. The average value of the slope over the five year period is 0.03 nT/°. Although there is no systematic variation in the slope from year to year, the data suggest a solar cycle dependence with a slightly stronger gradient near solar minimum, 1985-6.

Inspection of Table 1 reveals that the average values of Br for positive and negative sectors agree remarkably well. In four out of five years the difference between the average value in the positive and negative sector is within the average standard error for that year, strong evidence for the absence of an asymmetry in the field magnitude.

In figure 4 the results of this study are compared with existing models. Data from all five years of the study are superposed on the predicted relative variation in Br. The abrupt reversal in the sign of Br is also consistent with the current sheet model of Wolfson and the MHD model of Pneuman and Kopp, but inconsistent with the gradual variation that typifies the source surface models. The observed gradient in Br is qualitatively consistent with that predicted by the Pneuman and Kopp model and consistent with recent models modified to account for the recent Ulysses high-latitude observations, [cf., Zhao and Hoeksema, 1995].

The absence of an asymmetry in field strength between the northern and southern hemispheres contradicts the earlier studies of interplanetary data. The nature of the gradient is also inconsistent with that predicted by Luhmann. For that model, not only is the field stronger in one hemisphere, but the gradient reverses sign at the sector boundary, indicating that the field gets weaker toward the pole in one hemisphere and stronger in the other. The cause of these inconsistencies is uncertain at present but is presumably a consequence of the analysis approach that was used. We have concentrated on B_r rather than $|B_r|$ or other possible choices and have avoided averaging over intervals containing multiple current sheet crossings.

During the interval of this study, solar minimum and the ascending phase of the solar cycle, the dipole term is the dominant component in the expansion of the solar magnetic field. This is confirmed by the two-sector structure observed in the polarity pattern of the interplanetary magnetic field data (not shown). Our method of determining magnetic latitude relies on simplification of the actual source surface neutral line contour into a neutral line that represents only the dipole term. The merit of this method depends on the strength of the dipole term relative to the higher order terms in the spherical harmonic expansion of the solar magnetic field. Although during much of the solar cycle the simple notion of a tilted dipole is incorrect, near solar minimum, the dipole is the dominant term and our simplification should prove a good approximation. Whether or not our results apply to other phases of the solar cycle remains to be investigated.

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Table 1. Slope, intercept and correlation coefficient (r) for a linear fit to data above and below the current sheet separately for each year. The average valuefor each sector is also shown. The last column is the average standard error for the year.

	positive			negative			
Year	slope (nT/°)	intercept (nT)	r	Slope (nT/°)	intercept (nT)	r	s.e.
84	.027	3.52	.60	.011	-4.54	.29	.29
85	.021	2.83	.55	.040	-2.67	.62	.23
86	.041	2.59	.60	.046	-2.24	.69	.24
87	.040	2.61	.63	.025	-3.12	.36	.29
88	.024	2.50	.59	.028	-2.91	.36	.41

Table 1

Figure Captions

Figure 1. From Wolfson [1985] comparing the variation in B_r for three solar magnetic field models. The field **associated** with the source surface model varies gradually as the sine of the solar latitude. The model of Wolfson, which includes the current sheet, predicts a constant field magnitude which reverses abruptly at the sector boundary. The M 11 D model of Pneuman and Kopp [1921] predicts both a stronger field at high latitude and an abrupt reversal of the field across the current sheet.

Figure 2a. Source surface neutral line contours [Hoeksema, 1986] used to determine magnetic latitude. Barrington rotation 1753 in 1984 is shown. The sinusoidal variation of the neutral line is characteristic of that part of the solar cycle when the dipole term is dominant. The longitude of the dipole is assumed to be 180° from the midpoint between the ascending and descending crossings of the neutral line contour with zero degrees latitude. For this solar rotation it is at 60° Carrington longitude. The colatitude of the solar dipole is equal to the pseudoinclination, 43°.

Figure 2b. The idealized neutral line topology derived from the source surface contour of panel a.

Figure 3. Five degree magnetic latitude bin averages of the radial component of the magnetic field from ICE (closed circles) and 1 MP-8 (open circles), both at 1 AU. The data is shown separately for the years 1.984 through 1988. The error bars denote the standard error of the bin. The dashed lines are the averages for each sector.

Figure 41. Similar to figure 3 except here data from all years 1984-88 are plotted on the same panel. Linear fits to the data (dashed line) give $Br = .027(0) + 2.87$ and $Br = .032(0) - 3.08$ (where θ is the magnetic latitude) for data shove and below the current sheet respectively. Also shown are the field variations characteristic of the models of Wolfson (solid line) and the M I ID model of Pneuman and Kopp.

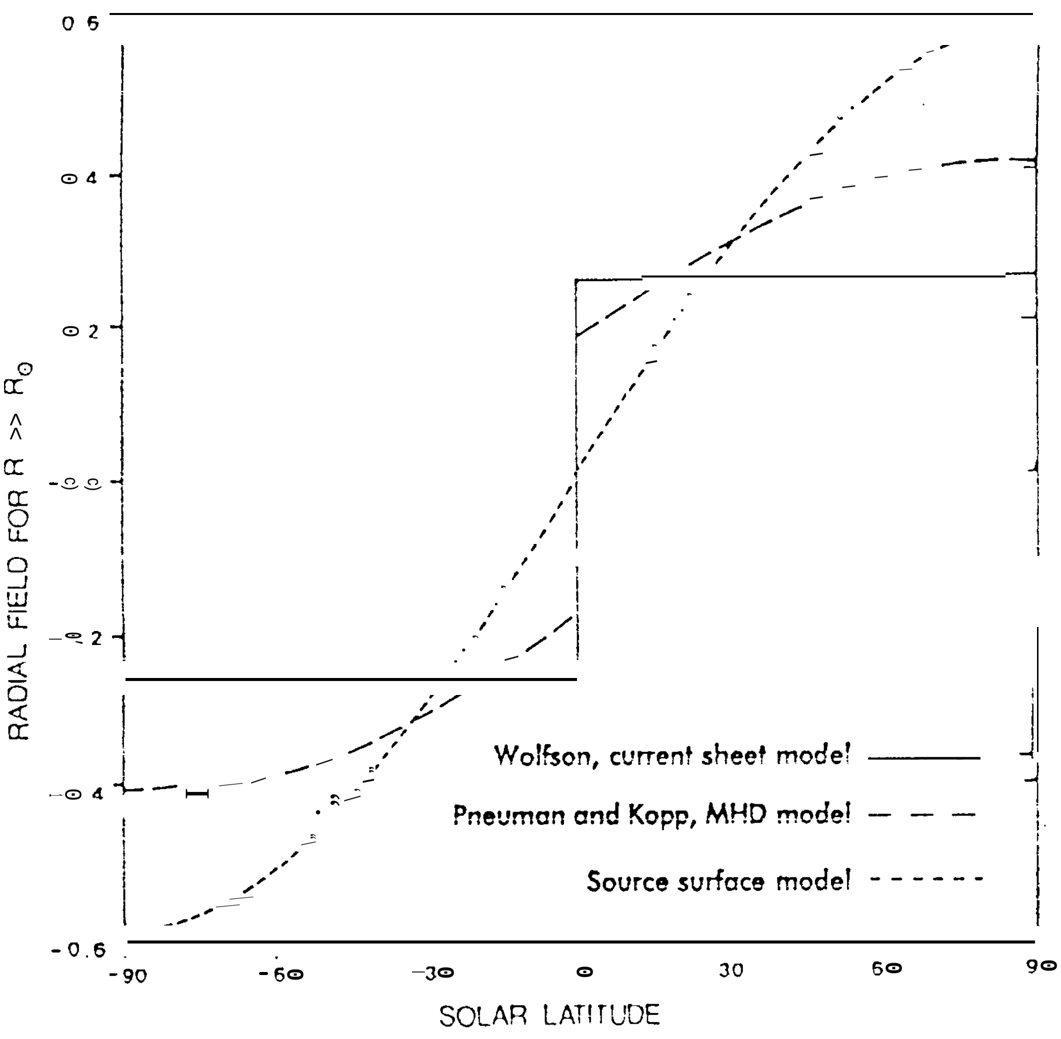
0 6
0 4
0 2
-0 0
-0 2
-0 4
-0.6
-90
-60
-30
0
30
60
90
RADIAL FIELD FOR R >> R$_\odot$
SOLAR LATITUDE
Wolfson, current sheet model
Pneuman and Kopp, MHD model
Source surface model

figure 1

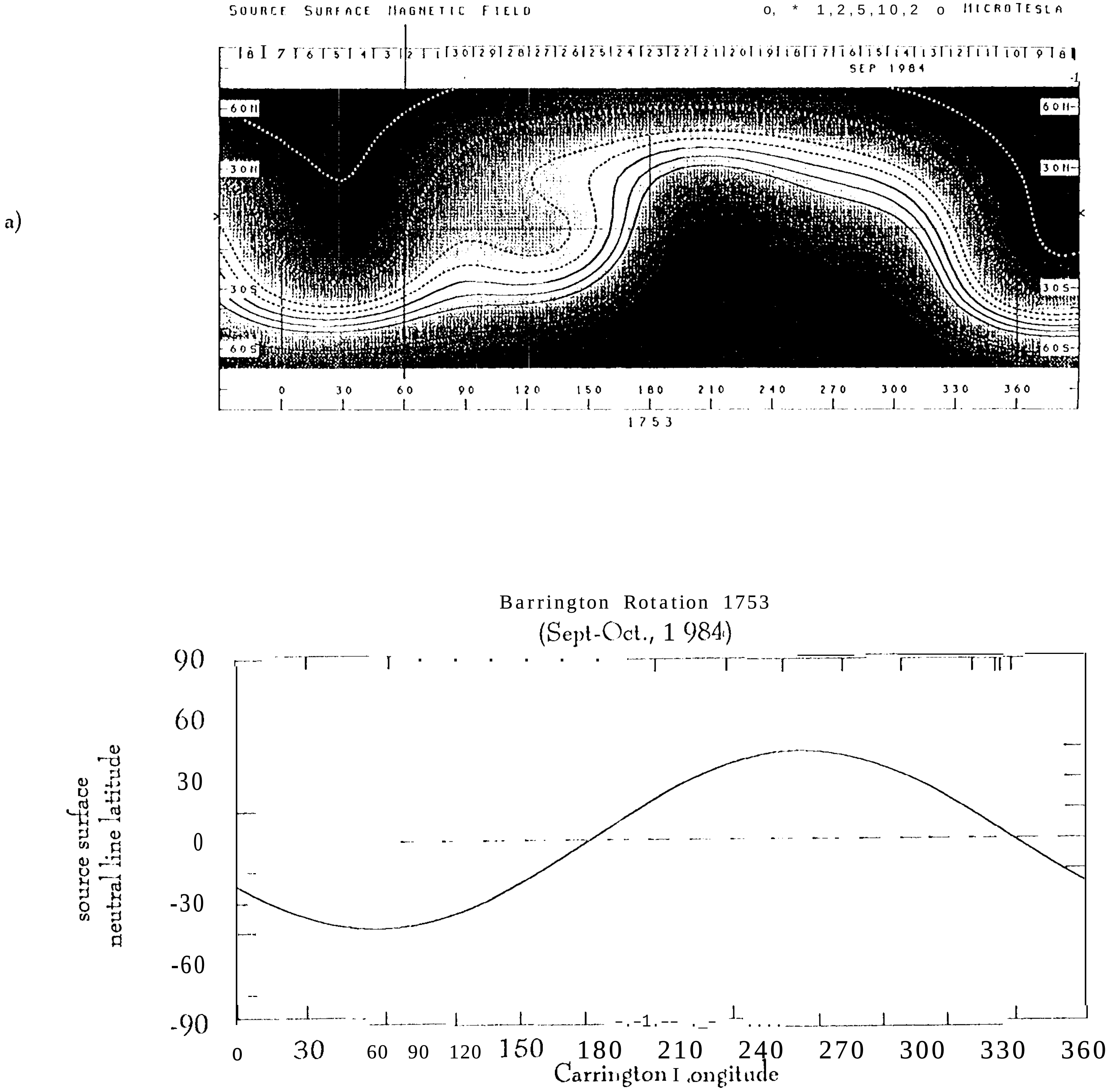
a)
SOURCE SURFACE MAGNETIC FIELD
0, * 1,2,5,10,2 0 MICROTESLA
SEP 1984
60N
30N
30S
60S
0 30 60 90 120 150 180 210 240 270 300 330 360
1753
b)
Barrington Rotation 1753
(Sept-Oct., 1 984)
source surface
neutral line latitude
90
60
30
0
-30
-60
-90
0 30 60 90 120 150 180 210 240 270 300 330 360
Carrington Longitude

figure 2

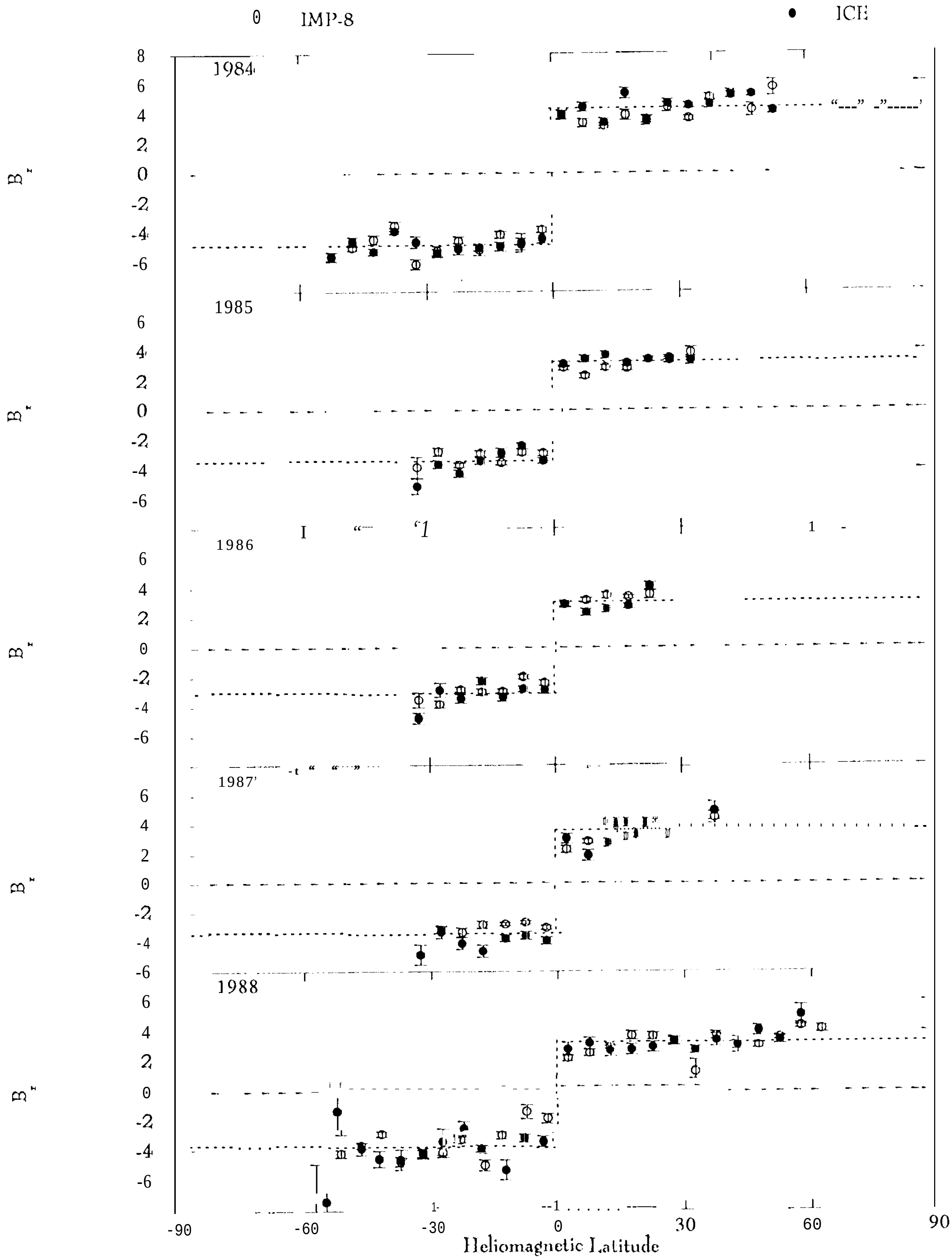
○ IMP-8
● ICE
1984
1985
1986
1987
1988
B_r
8
6
4
2
0
-2
-4
-6
-90
-60
-30
0
30
60
90
Heliomagnetic Latitude

figure 3

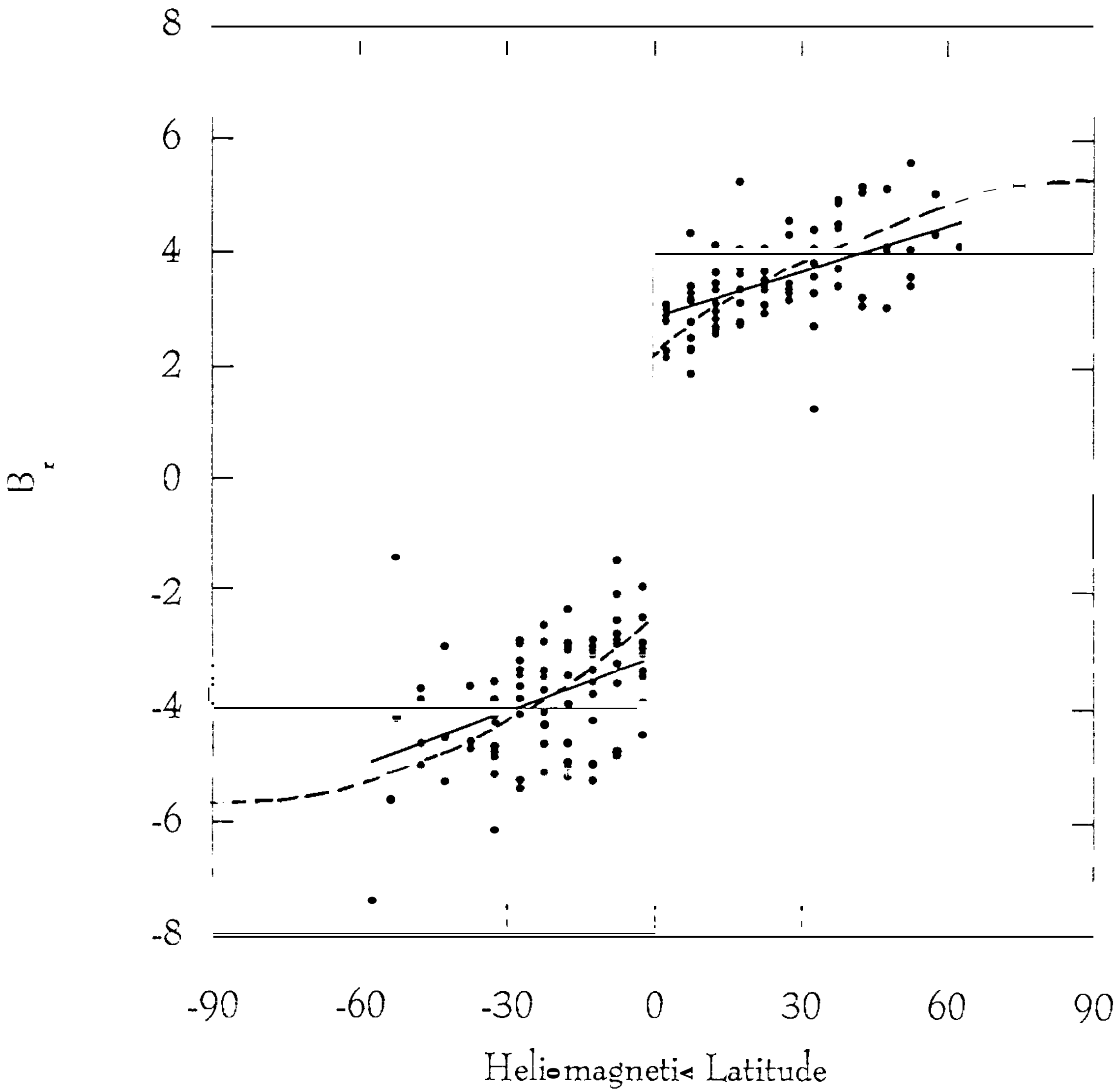

figure 4