THE ASTROPHYSICAL JOURNAL, 447:L143–L146, 1995 July 10

SOLAR IMPLICATIONS OF *ULYSSES* INTERPLANETARY FIELD MEASUREMENTS

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Received 1995 March 29; accepted 1995 April 27

ABSTRACT

Recent observations by the *Ulysses* magnetometer team have shown that the strength of the radial interplanetary field component, $|B_r|$, is essentially independent of latitude, a result which implies that the heliospheric currents are confined entirely to thin sheets. Using such a current sheet model, we extrapolate the observed photospheric field to 1 AU and compare the predicted magnitude and sign of B_r with spacecraft measurements during 1970–1993. Approximate agreement can be obtained if the solar magnetograph measurements in the Fe I λ5250 line are scaled upward by a latitude-dependent factor, similar to that derived by Ulrich from a study of magnetic saturation effects. The correction factor implies sharply peaked polar fields near sunspot minimum, with each polar coronal hole having a mean field strength of 10 G.

Subject headings: interplanetary medium — solar wind — Sun: corona — Sun: magnetic fields

1. INTRODUCTION

A principal objective of the *Ulysses* mission has been to obtain information about the Sun's polar regions by observing the high-latitude heliosphere (see, e.g., Balogh et al. 1992; Forsyth 1995). The *Ulysses* magnetometer team has shown recently that the strength of the radial interplanetary field component, $|B_r|$, is essentially independent of heliographic latitude λ (Balogh et al. 1995). This result is consistent with a "split monopole" configuration in which the heliospheric currents are confined to thin sheets, where B_r abruptly reverses its sign without changing its magnitude (see, e.g., Parker 1963; Schatten 1971; Schulz, Frazier, & Boucher 1978; Wolfson 1985; Wang & Sheeley 1988). Such a configuration is established after latitudinal flows in the solar wind have smoothed out the transverse gradients in the magnetic pressure (see Suess & Nerney 1975). In the coronal hole model of Suess et al. (1977), the radial field component becomes essentially independent of λ at a heliocentric distance $r \sim 5\ R_\odot$; however, their MHD calculations also suggested that latitudinal gradients in $|B_r|$ could be reestablished at greater distances from the Sun, depending on the assumed temperature variation across the hole. Such gradients appear in the global MHD model of Pneuman & Kopp (1971), where (for large r) $|B_r|$ declines by a factor of 2 between the pole and the equator (see Fig. 3 in Wolfson 1985).

By extrapolating photospheric field measurements taken in the Fe I λ5250 line, Wang & Sheeley (1988) were able to match the observed long-term variation of $|B_r|$ near Earth by postulating the presence of both volume and sheet currents, as predicted by Pneuman & Kopp (1971). However, the substantial latitudinal gradients in $|B_r|$ implied by the volume currents (Wang 1993; Zhao & Hoeksema 1995) are inconsistent with the observations of Balogh et al. (1995).

Here we show that both the magnitude and sign of the interplanetary B_r can be reproduced without requiring volume currents, provided that the solar magnetograph measurements are corrected by a saturation factor that varies from center to limb, as deduced by Ulrich (1992). We also discuss the implications of such a correction factor for the strength and distribution of the Sun's high-latitude fields.

2. EVIDENCE FOR A LATITUDE-DEPENDENT SATURATION FACTOR

It is now widely accepted that much of the photospheric magnetic field is concentrated at the supergranular cell boundaries in unresolved bundles having characteristic field strengths of order 10^3 G (see, e.g., Zwaan 1987). In magnetograph measurements using the Fe I λ5250 line, the Zeeman splitting corresponding to such field strengths is comparable to the line width, causing a reduction in the magnetograph signal (Howard & Stenflo 1972; Frazier & Stenflo 1972); there is also a weakening of the line as a result of the increased temperatures within the flux bundles (Chapman & Sheeley 1968; Livingston & Harvey 1969). The net result is that the magnetograph signal no longer scales linearly with the line-of-sight field component B_l and becomes "saturated." To obtain the true line-of-sight field strength (averaged over the scanning aperture), it is customary to employ a broader and magnetically less sensitive line such as Fe I λ5233, which also has the advantage of being less temperature dependent than the Fe I λ5250 line.

By performing simultaneous observations in Fe I λλ5250, 5233 with the Mount Wilson Observatory (MWO) magnetograph, Ulrich (1992) derived a correction factor for the magnetic fluxes from the 5250 Å line as a function of both center-to-limb angle ρ and aperture size. For large apertures (comparable to the supergranular scale), the factor δ^{-1} by which the "saturated" 5250 Å fluxes must be multiplied to convert them into "unsaturated" 5233 Å fluxes varies approximately as (see Fig. 1)

$$\delta^{-1}(\lambda) = 4.5 - 2.5 \sin^2 \lambda. \quad (1)$$

Since we will be employing synoptic data weighted around central meridian, we have here replaced the center-to-limb angle of Ulrich (1992) by an equivalent latitude λ. According to equation (1), the saturation factor declines from a value of ~4.5 near the equator to a value of ~2 near the poles. This decrease can be attributed to the fact that, toward the limb, the magnetograph signal originates higher in the atmosphere, where the field is weaker and the temperature lower (Howard & Stenflo 1972). (It should be noted that, although the field strength declines due to the rapid fanning out of field lines at

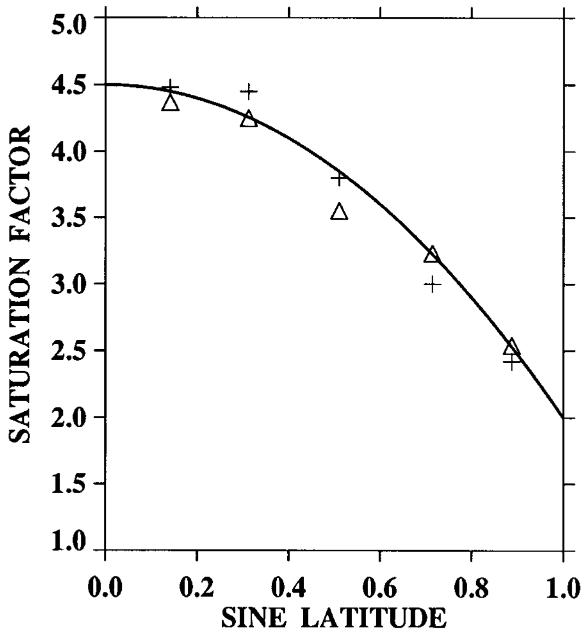

FIG. 1.—Latitude dependence of the saturation correction (δ^{-1}) for photospheric magnetic fluxes measured in the Fe I λ5250 line, based on MWO observations by Ulrich (1992). δ^{-1} is the factor by which the saturated Fe I λ5250 fluxes must be multiplied to convert them into unsaturated Fe I λ5233 fluxes. *Triangles* (*crosses*): results for an aperture size or spatial resolution of 12″ × 12″ (20″ × 20″). *Solid curve*: an approximate fit to the data points of the form $\delta^{-1}(\lambda) = 4.5 - 2.5 \sin^2 \lambda$.

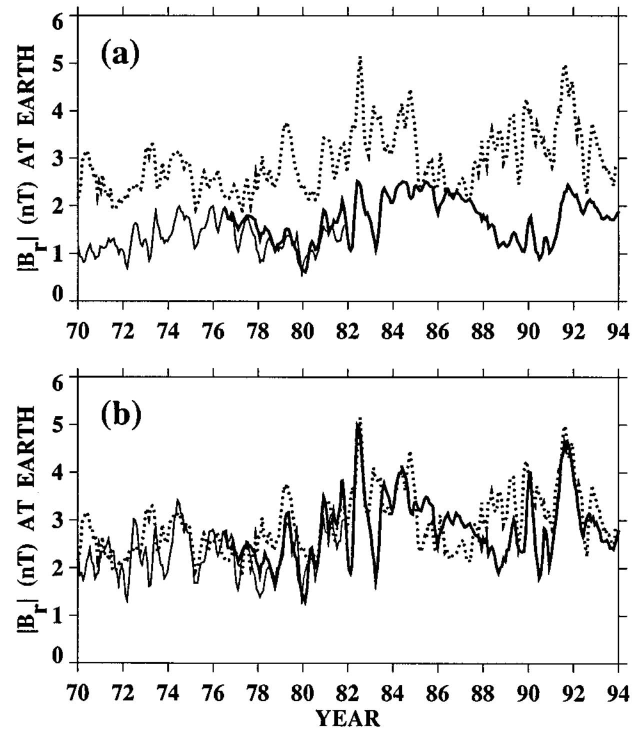

FIG. 2.—Three month running averages of the observed and calculated radial field intensity at Earth during 1970–1993. *Dotted lines*: spacecraft measurements (NSSDC OMNI data). *Thin solid lines*: "current sheet" extrapolation of MWO synoptic data during 1970–1981. *Thick solid lines*: "current sheet" extrapolation of WSO synoptic data during 1976–1993. (*a*) Both the MWO and WSO photospheric fields scaled upward by a constant factor $\delta^{-1} = 1.8$. (*b*) Both fields scaled upward by a latitude-dependent factor $\delta^{-1} = 4.5 - 2.5 \sin^2 \lambda$. Models assume that the interplanetary flux is distributed isotropically at 1 AU.

the network boundaries, the net *flux* contained within an aperture that averages over one or more supergranules is not expected to change significantly with height.)

A very different behavior for δ^{-1} was inferred by Svalgaard, Duvall, & Scherrer (1978) using the Wilcox Solar Observatory (WSO) magnetograph in conjunction with the Fe I λ5250 line and a 175″ × 175″ aperture. They found that the average line-of-sight photospheric field varied in direct proportion to cos ρ, as expected if the center-to-limb variation was determined by simple line-of-sight projection. They concluded, therefore, that the saturation factor was independent of ρ and adopted a constant value $\delta^{-1} = 1.8$.

Although we are unable to explain the discrepancy between the MWO and WSO results, we may ask whether either form of δ^{-1}, applied to the long-term 5250 Å synoptic data from the two observatories, allows us to reproduce the variation of $|B_r|$ measured at Earth. Since the interplanetary flux is distributed isotropically, $|B_r|$ varies in proportion to $|\Phi_{\rm open}|$, the total amount of "open" flux on the Sun. We calculate $|\Phi_{\rm open}|$ from the observed photospheric field using the potential-field source-surface (PFSS) procedure (Schatten, Wilcox, & Ness 1969), which successfully reproduces observed coronal hole areas (Wang & Sheeley 1992). Here the coronal field is assumed to remain current free between the solar surface $r = R_\odot$ and a spherical "source surface" $r = R_s$, where the field lines are constrained to be radial. At $r = R_\odot$, the radial component of this potential field is matched to the observed photospheric field, after the latter has been corrected for line-of-sight projection (by dividing by cos λ) and for saturation effects (by multiplying by δ^{-1}). The radial field intensity at Earth ($r = r_{\rm E} = 215\ R_\odot$) is given by

$$|B_{\rm E}| = \frac{|\Phi_{\rm open}|}{4\pi r_{\rm E}^2} = \frac{1}{4\pi}\left(\frac{R_s}{215\ R_\odot}\right)^2 \int |B_r(R_s, \lambda, \phi)|\, d\Omega, \qquad (2)$$

where ϕ denotes longitude, the integral is over all solid angle Ω at the source surface, and we shall henceforth set $R_s = 2.5\ R_\odot$ (see Hoeksema 1984; Wang & Sheeley 1988).

Figure 2 compares the observed variation of $|B_{\rm E}|$ with that derived using synoptic 5250 Å data from MWO during 1970–1981 and from WSO during the overlapping period 1976–1993. Only pre-1982 MWO data were used because of possible calibration problems affecting the Mount Wilson magnetograph when it was rebuilt at the end of 1981 (see Figs. 8 and 9 of Wang & Sheeley 1988). In the extrapolations shown in Figure 2*a*, both the MWO and WSO photospheric fields have been multiplied by a constant factor $\delta^{-1} = 1.8$. In this case, the derived $|B_{\rm E}|$ variation is characterized by a broad maximum during the declining phase of each sunspot cycle and a minimum near sunspot maximum (1979–1980, 1989–1990), when the calculated field strengths are 2–3 times lower than the observed ones. In Figure 2*b*, both the MWO and WSO photospheric fields have been multiplied by the latitude-dependent saturation factor (eq. [1]). In this case, we obtain a reasonably good match to the observed $|B_{\rm E}|$ variation through most of the 24 yr interval. The improvement over Figure 2*a* is a result of the fact that the low-latitude photospheric fields, which provide the dominant contribution to Φ_{open} and B_E near sunspot maximum, have now been scaled upward by a factor $\sim$4.5 rather than 1.8.

From Figures 2*a* and 2*b*, we note that the extrapolated MWO and WSO fields show good agreement with each other during their period of overlap (1976–1981), whereas this agreement would not have existed had a different correction factor been applied to each data set. On the basis of Figure 2*b*, we suggest that both the MWO and the WSO synoptic data should be scaled upward by a latitude-dependent factor similar to equation (1).

As a further test, we may ask if equation (1) is consistent with the variation of the interplanetary sector polarity at Earth. To derive the sign (rather than the magnitude) of B_E, we suppose again that the coronal field can be approximated by the PFSS model for $r \leq R_s = 2.5\ R_\odot$. In the region $r > R_s$, we now introduce sheet currents by matching the radial component of a potential field (including an r^{-2} monopole contribution) to $|B_r(R_s, \lambda, \phi)|$ and then restoring the original direction of the field lines, as proposed by Schatten (1971). The resulting current sheets (which can be located by field-line tracing) will generally not have a radial orientation near the Sun. Although the matching procedure gives rise to a tangential field discontinuity at $r = R_s$, the error in the integrated flux $|\Phi_{open}|$ is quite small ($\sim$13%), as suggested by self-consistent calculations involving axisymmetric current sheets (see Table I in Sheeley, Wang, & Harvey 1989).

We have applied this "current sheet" (CS) model to the WSO photospheric fields, after correcting them for line profile saturation using equation (1). Figure 3 (Plate L26) displays the calculated and observed interplanetary sector patterns at Earth during 1976–1993. Also shown are the polarity patterns derived by applying the standard PFSS model (in which the field lines remain purely radial for $r \geq R_s$) to the *uncorrected* WSO fields. On the whole, the two models yield surprisingly similar results, and both are quite successful at reproducing the observed sector patterns. The main differences are seen near sunspot minimum, when the polar fields reach their peak strength and the neutral sheet lies near the ecliptic: the PFSS model yields somewhat better agreement with the observations during 1976–1977, whereas the CS model is substantially better during 1985–1987.

As a final test, we simulate the variation of the interplanetary sector polarity along the 1990–1993 trajectory of *Ulysses*, as determined by Balogh et al. (1993) and Smith et al. (1993). Figure 4 (Plate L27) displays the observed sector polarities at *Ulysses*, along with the B_r polarities derived from the WSO photospheric fields by the following procedures: CS model, latitude-dependent correction given by equation (1); CS model, no correction; PFSS model, no correction. Both the PFSS and the "corrected" CS model show good agreement with *Ulysses*; in particular, they predict that the heliospheric current sheet should extend to latitude 29°S, while *Ulysses* in fact observed the positive-polarity sector to vanish above latitude $\sim$27°S. By contrast, the "uncorrected" CS model has the positive-polarity sector disappearing far too soon; the current sheet is too flat in this case because the relative amount of low-latitude photospheric flux has apparently been underestimated.

In comparison with the original PFSS model, the sheet currents tend to make the magnetic neutral sheet flatter by pulling axisymmetric flux from the Sun's polar regions toward the equator. On the other hand, the saturation correction (eq.

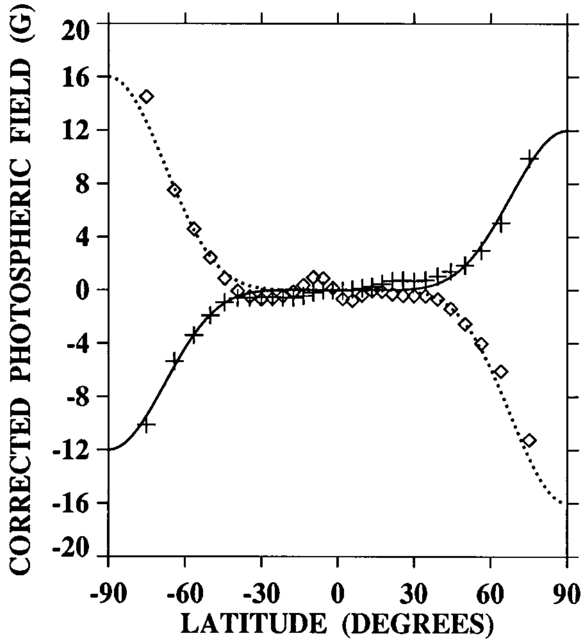

FIG. 5.—Latitudinal distribution of the photospheric field at sunspot minimum. WSO synoptic data were divided by cos λ to correct for projection, multiplied by the latitude-dependent saturation factor in eq. (1), and averaged over longitude. *Plus signs* (*diamonds*): the resulting flux distribution averaged over 1976 (1986). Curves indicate approximate fits to the data points of the form $B_0 \sin^7 \lambda$, where $B_0 = 12$ G during 1976 (*solid line*) and $B_0 = -16$ G during 1986 (*dotted line*).

[1]) tends to make the neutral sheet less flat by increasing the strength of the low-latitude photospheric fields, which provide the main contribution to the nonaxisymmetric harmonic components (including, in particular, the equatorial dipole component) of the coronal field. The qualitative agreement between the corrected CS model and the uncorrected PFSS model in Figures 3 and 4 is due to the mutual cancellation of these opposing effects.

3. THE POLAR FIELDS

From the *Ulysses* observation that the Sun's open magnetic flux is distributed uniformly and from the saturation correction (eq. [1]), we may derive some important properties of the photospheric field. The relative constancy, to within a factor of $\sim$2, of $|B_r|$ at Earth (King 1979; Slavin, Jungman, & Smith 1986) reflects the relative constancy of $|\Phi_{open}|$. As shown by Figure 2, both quantities attain their peak values $\sim$2 yr after sunspot maximum, at the time when the new polar holes are formed. Adopting $|B_r| \sim 3\ nT$ ($= 3 \times 10^{-5}$ G) as a typical radial field intensity at 1 AU, we deduce that $|\Phi_{open}| = 4\pi r_E^2|B_r| \sim 8 \times 10^{22}$ Mx, equivalent to the total flux contained within two polar holes each with a mean field strength of 10 G and latitudinal extent of 30°.

Figure 5 shows the latitudinal distribution of the photospheric field at sunspot minimum. Here we have applied the latitude-dependent scaling factor (eq. [1]) to the WSO synoptic data during 1976 and 1986, corrected for line-of-sight projection by dividing by cos λ, and averaged the fields over longitude. As indicated by the curve fits, the latitudinal variation can be approximated by a function of the form $\langle B_r(R_\odot, \lambda)\rangle = B_0 \sin^7 \lambda$, where $B_0 = 12$ G (-16 G) in 1976 (1986). This result is qualitatively similar to that obtained by Svalgaard et al. (1978), even though they assumed a constant scaling factor of 1.8. It is also consistent with the polar field strength of ~20 G that Suess et al. (1977) inferred by modeling the polar hole observations of Munro & Jackson (1977). As discussed by Wang, Nash, & Sheeley (1989), the maintenance of such sharply peaked polar fields requires the presence of a poleward meridional flow on the Sun.

4. CONCLUSIONS

The main points of this Letter may be summarized as follows:

1. The absence of latitudinal gradients in $|B_r|$ reported by the *Ulysses* magnetometer team implies that the heliospheric currents are entirely confined to thin sheets, unlike in the PFSS model or the MHD model of Pneuman & Kopp (1971), where latitudinal gradients are maintained by volume currents.

2. To reproduce the observed long-term variation of $|B_r|$ at Earth using a current sheet model, we find that a latitude-dependent correction factor similar to that derived by Ulrich (1992) must be applied to synoptic photospheric-field measurements in the Fe I λ5250 line. This correction for line profile saturation increases the relative strength of the low-latitude photospheric fields.

3. When the correction factor is used in conjunction with a current sheet model, we are able to match the interplanetary sector structure both in the ecliptic and along the trajectory of *Ulysses*. The agreement is comparable to or better than that obtained with the original PFSS model.

4. Since the radial field intensity at Earth varies in proportion to the total amount of open flux on the Sun, the surprisingly modest variation of $|B_r|$ observed during the solar cycle reflects a similar lack of variation of $|\Phi_{\rm open}|$ ($\sim 8 \times 10^{22}$ Mx).

5. The polar fields have a "topknot" distribution near sunspot minimum ($B \sim B_0 \sin^7 \lambda$, where $|B_0| \sim 12$–16 G), with the average field strength inside each polar coronal hole being about 10 G.

We are indebted to A. Balogh, G. Erdös, R. J. Forsyth, and E. J. Smith for informative discussions and for providing the data shown in Figure 4. We also thank R. K. Ulrich for useful comments on line profile saturation and J. T. Hoeksema for making available the WSO photospheric data. This work was supported by NASA and the Office of Naval Research.

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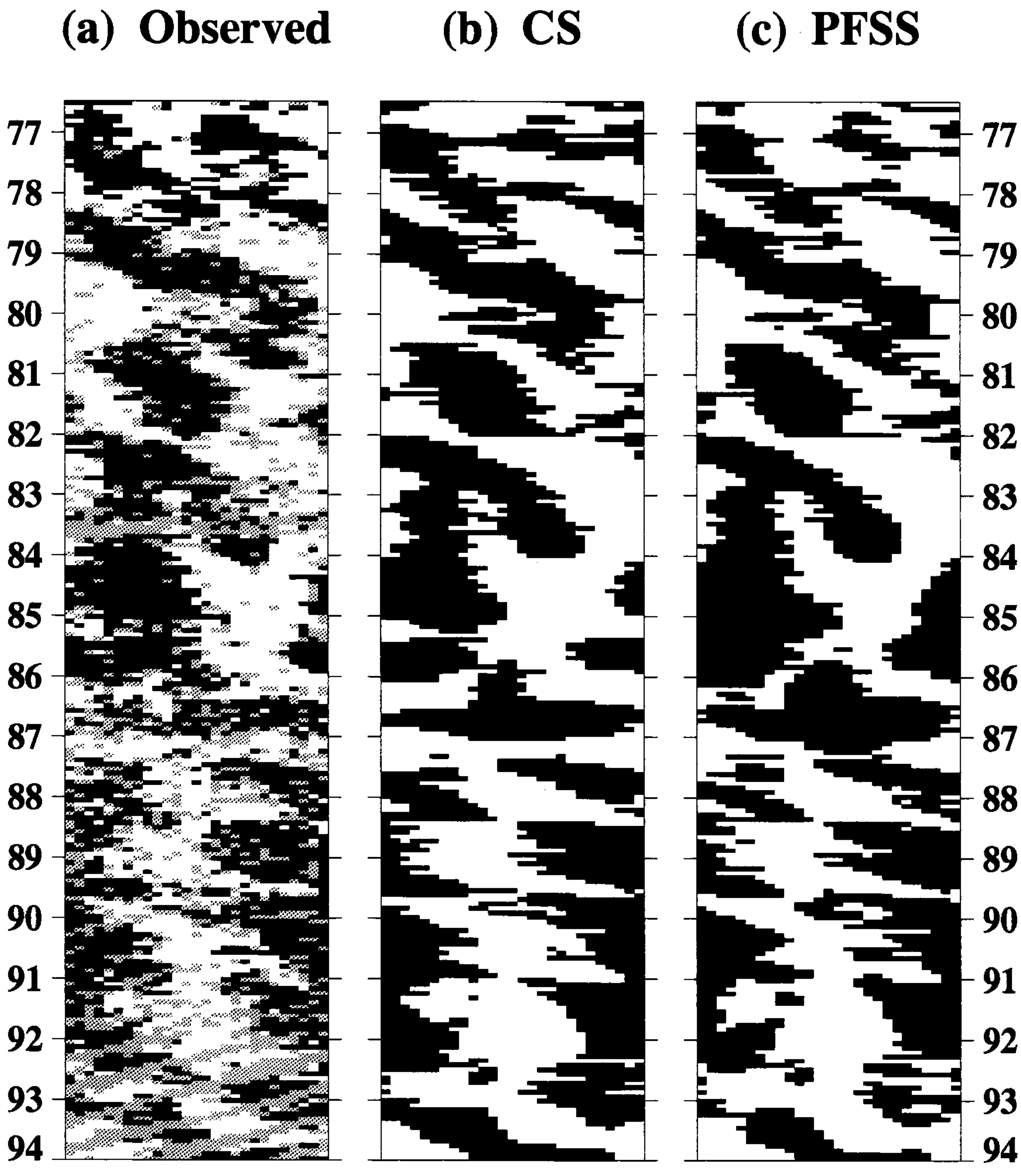

FIG. 3.—Variation of the interplanetary sector polarity at Earth (1976–1993). Daily averaged polarities are plotted in 27 day rows (Bartels format), with white (black) denoting magnetic fields that point outward from (inward toward) the Sun. (*a*) Observed polarities (NSSDC OMNI data); here gray indicates data gaps or uncertain polarities. (*b*) Polarities derived by applying a current sheet model to the WSO synoptic data, corrected for saturation using the latitude-dependent factor in eq. (1). (*c*) Polarities derived by applying the standard potential-field source-surface model to the uncorrected WSO synoptic data. In panels (*b*) and (*c*), the Sun-Earth transit time for the solar wind was assigned an average value of 4 days.

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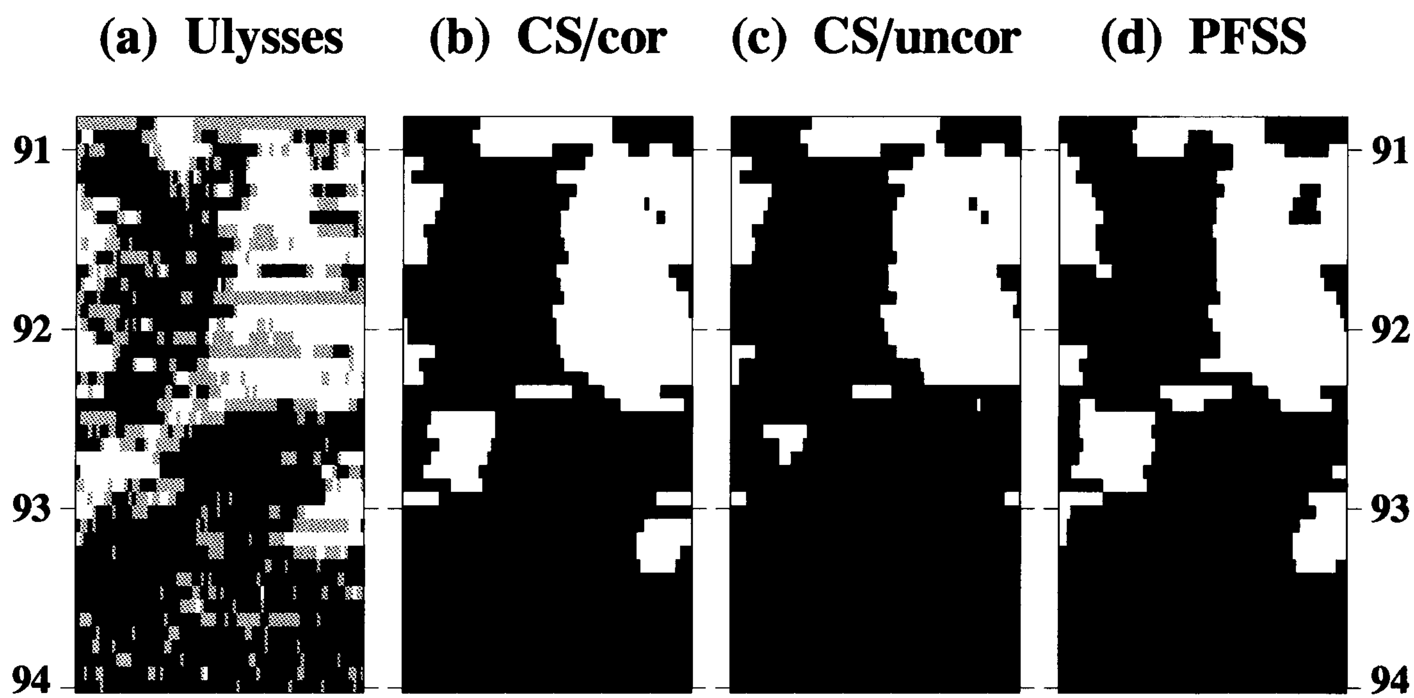

FIG. 4.—Interplanetary sector polarity along the orbital trajectory of *Ulysses* from its 1990 October injection to 1993 December, when the spacecraft was approaching heliographic latitude 50°S. Each row of pixels represents one 27.3 day Carrington rotation (starting from CR 1835), with Carrington longitude running from left to right. (*a*) Measured polarities (see Balogh et al. 1993), kindly provided by G. Erdös. White (black) denotes outward (inward) field; data gaps and uncertain polarities are gray. The assigned Carrington rotations and longitudes correspond to the time when the wind plasma observed at *Ulysses* left the Sun. (*b*) Current sheet model applied to WSO synoptic data with the latitude-dependent correction in eq. (1). (*c*) Current sheet model applied to the uncorrected WSO data. (*d*) Potential-field source-surface model applied to the uncorrected WSO data.

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