North-South Offset of Heliospheric Current Sheet and its Causes

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Abstract

Based on observations of the photospheric magnetic field we develop a method to estimate the north-south offset of the heliospheric current sheet with respect to both the magnetic and the heliographic equator. Examing the north-south offset obtained over 25 years we find that (1) The north-south offset of the heliospheric current sheet occurs alternatively in most of time between 1976 and 2001. Each offset of several degrees lasts usually for a few solar rotations; (2) There are two long southward offset of the heliospheric current sheet occurred between March 1983 and July 1986 and between April 1992 and May 1995; (3) The north-south offset of the heliospheric current sheet from Sun's equator depends on the asymmetry between north and south magnetic hemispheres in the areas of open field regions and the expansion rate of the areas from coronal base to the source surface. The sun's dipole tilt angle also affects the north-south offset from the heliographic equator. Near sunspot minimum, open field regions occur only in polar caps and Sun's dipole is basically parallel to Sun's rotation axis, the north-south offset of the heliospheric current sheet depends mainly on the asymmetry in the area or field strength between north and south polar coronal holes.

— The IAU XXV Assembly, JD07, July 16, 2003, Sydney

1. Introduction

Evidence of a southward displacement of 10° for the heliospheric current sheet (HCS) was first inferred from Ulysses cosmic-ray observations in the rapid transit from the south to north solar poles between September 1994 and May 1995 (Simpson et al., 1996). The computed neutral line on the classical source surface map, that agrees remarkably well with the set of HCS crossings observed by WIND and Ulysses, is indeed displaced southward, with latitudinal excursions raging from -22° to $+17^\circ$ (Crooker et al., 1997). An asymmetry of 10° in HCS is expected to have significant different magnitudes of radial field component in the Sun's north and south magnetic hemispheres. The heliospheric magnetic field measured by Ulysses during the rapid transit did show a slight asymmetry with the field strength in the south stronger than in the north. However, this asymmetry may be caused by temporal changes because measurements made by Ulysses during the first rapid south-north scan in the north hemisphere are obtained several months later than measurements made in the south hemisphere (McComas et al., 2000). To address this ambiguity, the field in positive and negative sectors observed by WIND in ecliptic were compared, and a large difference of 30% in the radial component of the heliospheric magnetic field was observed between December 1994 and April 1995, with a larger radial component in the south than in the north and the large difference tended to disappear after May 1995 (Smith et al., 2000).

Does the southward displacement of the HCS occur during other intervals and phases of the solar cycle? What is the cause of the north-south asymmetry in the global heliosphere?

We first develop a method to estimate, from the solar observations, the offset of the HCS and the difference of the mean field between two hemispheres in Section 2, then predict the north-south offset of the HCS over two solar cycles using the WSO data in Section 3, and discuss the causes of the north-south offset of the HCS in Section 4, finally we summary the results in Section 5.

2. Method

In the potential field source surface model (PFSS) [*Schatten et al* 1969], the coronal field satisfies $\bigtriangledown \times B = 0$ out to a spherical "source surface" at $r = R_{ss} = 2.5R_{\odot}$, where the effect of the quasiradial solar-wind outflow is simulated by assuming that the field is radial pointed everywhere over the source surface. At the lower boundary $r = R_{\odot}$, the radial field component is matched to the photospheric field, which is assumed to be radially oriented [Wang and Sheeley, 1992; Zhao and Hoeksema, 1993]. By definition, all field lines that extend from $r = R_{\odot}$ to $r = R_{ss}$ are "open". The neutral line at the source surface and the open field regions at the coronal base derived using the PFSS model reproduce the global configuration of the HCS and coronal holes throughout the solar cycle (Hoeksema et al., 1982; Wang et al, 1996; Zhao and Hoeksema, 1999; Zhao et al. 2002).

The displacement of the HCS southward from the heliographic equator implies that the solid angle corresponding to the source surface area occupied by the south magnetic hemisphere is less than that occupied by the north magnetic hemisphere. The solid angles of south and north magnetic hemispheres, Ω_{ss}^{S} and Ω_{ss}^{N}, can be expressed

$$\Omega_{ss}^{NS} = \sum_{i=1}^{I^{NS}} \delta\Omega_{ssi} \tag{1}$$

where symbol NS denotes N or S for north or south magnetic hemisphere, $\delta\Omega_{ssi}$ the solid angle element, and I^{NS} the number of solid angle elements in the north or south magnetic hemisphere, i.e., I^{N} or I^{S}. Using the equally spaced grid size for $cos\theta$ and ϕ (θ and ϕ denote the colatitude and Carrington longitude), for example, $\Delta\phi = 2\pi/72$ and $\Delta(cos\theta) = 2/30$ for WSO data, the solid angle element $\delta\Omega_{ssi} = \Delta(cos\theta) \cdot \Delta\phi = 4\pi/2160 = \delta\Omega_{ss}$. Equation (1) becomes

$$\Omega_{ss}^{NS} = I^{NS}\delta\Omega_{ss} \tag{2}$$

The solid angles north and south for a warped HCS may be estimated using a flat HCS displaced of λ_m from the magnetic equator

$$\Omega_{ss}^{NS} = 2\pi(1 \mp \sin\lambda_m) \tag{3}$$

Based on Equations (2) and (3) the offset of the HCS from the magnetic equator can be calculated using I^N and I^S,

$$\lambda_m = sin^{-1}\frac{I^S - I^N}{I^S + I^N} \tag{4}$$

The heliospheric magnetic field is determined by lower multiple magnetic moments of the photospheric magnetic field. The Sun's dipole component usually has a tilt angle, δ, relative to the Sun's rotation axis. The displacement of the HCS from the heliographic equator, λ, is thus

$$\lambda = \lambda_m \cos\delta \tag{5}$$

Here the tilt angle of the Sun's dipole

$$\delta = \tan^{-1}\frac{\sqrt{g_{11}^2 + h_{11}^2}}{g_{10}} \tag{6}$$

where g_{10}, g_{11} and h_{11} are the first degree spherical harmonic coefficients, and can be obtained using the global distribution of the radial photospheric magnetic field. The tilt angle is increased from 0° at sunspot minimum through 90° at maximum to 180° at next minimum, and then return to 0° in the next next minimum. The magnetic polarity in the south (north) magnetic hemisphere is also changed around sunspot maximum from one solar cycle to the next, and is negative (positive) when $g_{10} > 0$ and positive (negative) when $g_{10} < 0$.

The total source surface areas and the total source surface magnetic flux in the south and north magnetic hemispheres

$$A_{ss}^{NS} = I^{NS} R_{ss}^2 \delta\Omega_{ss} \tag{7}$$

$$\Phi_{ss}^{NS} = R_{ss}^2 \delta\Omega_{ss} \sum_{i=1}^{I^{NS}} B_{ssi}^{NS} \tag{8}$$

where B_{ssi}^{NS} denotes the source surface field strength. The mean source surface field strength over south and north magnetic hemispheres, $\overline{B_{ss}^{NS}}$ is

$$\overline{B_{ss}^{NS}} = \frac{\Phi_{ss}^{NS}}{A_{ss}^{NS}} = \frac{\sum_{i=1}^{I^{NS}} B_{ssi}^{NS}}{I^{NS}} \tag{9}$$

Since the total magnetic flux in the south magnetic hemisphere must be equal to the total magnetic flux in the north magnetic hemisphere, the ratio of the mean field over the south hemisphere to the mean field over the north hemisphere can be estimated

$$\xi = \frac{\overline{B_{ss}^{S}}}{\overline{B_{ss}^{N}}} = \frac{I^N}{I^S}. \tag{10}$$

3. The predicted north-south asymmetry in the heliosphere

To estimate the north-south asymmetry in the global heliospheric magnetic field on the bases of Equations (4), (5) and (10) we extrapolate the observed photospheric field into the corona using the PFSS model. For the photospheric field measurements, we employ Carrington synoptic charts from the Wilcox Solar Observatory (WSO) for the periods 1976–2001, and correct for the saturation of the Fe I 5250 $\AA$ line profile by multiplying the measured magnetic fluxes by the latitude dependent factor $4.5 - 2.5\sin^2\lambda$ [*Wang and Sheeley*, 1995].

Using the WSO synoptic chart for Carrington number of 1893 (between 23 Feb. and 23 March, 1995) and the PFSS model, we obtain the spherical harmonic coefficients and calculate Sun's dipole tilt angle and the magnetic field at the source surface. The magnetic polarity in south (north) magnetic hemisphere is negative (positive) in the period of time (Figure 1). We have $I^N = 1275$, $I^S = 885$, $\delta = 8.38°$, and obtain $\lambda_m = -10.40$, $\lambda = -10.29$, and $\xi = 1.44$. The calculated offset is the same as that inferred from Ulysses cosmic-ray observations in the first rapid transit (Simon, 1996), and the calculated mean source surface field ratio of 1.44 is also nearly the same as that inferred from WIND observations of heliospheric magnetic field in ecliptic, i.e., $3.5/2.5 = 1.40$ (Smith et al., 2000).

Is the southward displacement of the HCS observed by Ulysses and WIND spacecraft and reproduced by this model a normal phenomenon? We examine the north-south asymmetry for all Carrington rotations between 1976 and 2001 using WSO observations of the photospheric field.

Figure 2 shows the dipole tilt angle, δ (top panel), the solid angle of positive and negative hemispheres, Ω_{ss}^N and Ω_{ss}^S (second panel), the north-south displacement of the HCS from heliographic and magnetic equator, λ and λ_m (third panel), and the predicted IMF Br on the basis of $\overline{B_{ss}^{NS}}$. Figures 2 indicates that the north-south displacement of the HCS and the field strength asymmetry between north and south hemispheres are a normal phenomenon. A northward or southward displacement of several degrees from the heliographic equator occurs alternatively, each lasting usually for a few solar rotations. There are two long intervals of southward displacement, lasting more than 40 solar rotations and occurring between declining and minimum phases of solar activity. It should be noted that the second interval is ended in May 1995 and does not extend into sunspot minimum, consistent with the WIND measurements [Smith et al., 2000].

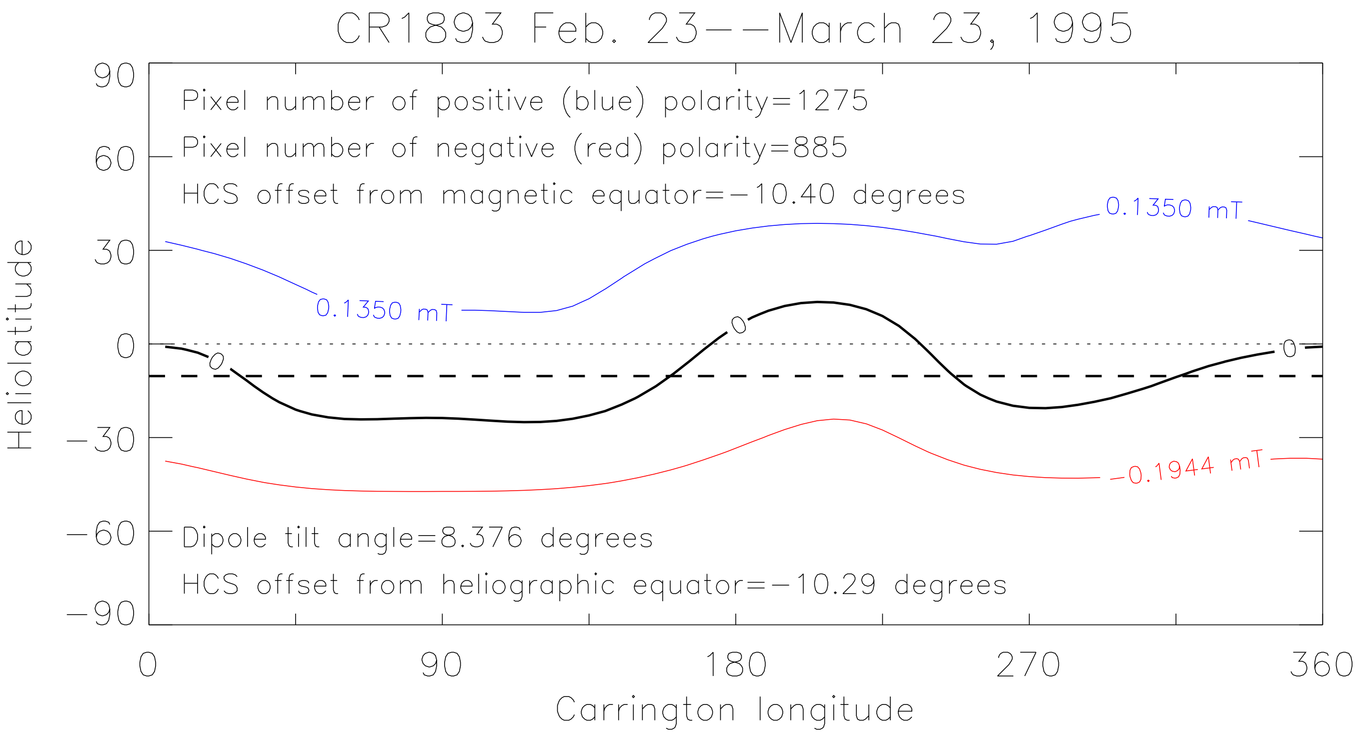

Fig. 1.— The computed neutral line (the thick solid curve) and its southward displacement (the thick dashed line) from the heliographic equator (the dotted line) for Carrington rotation of 1893.

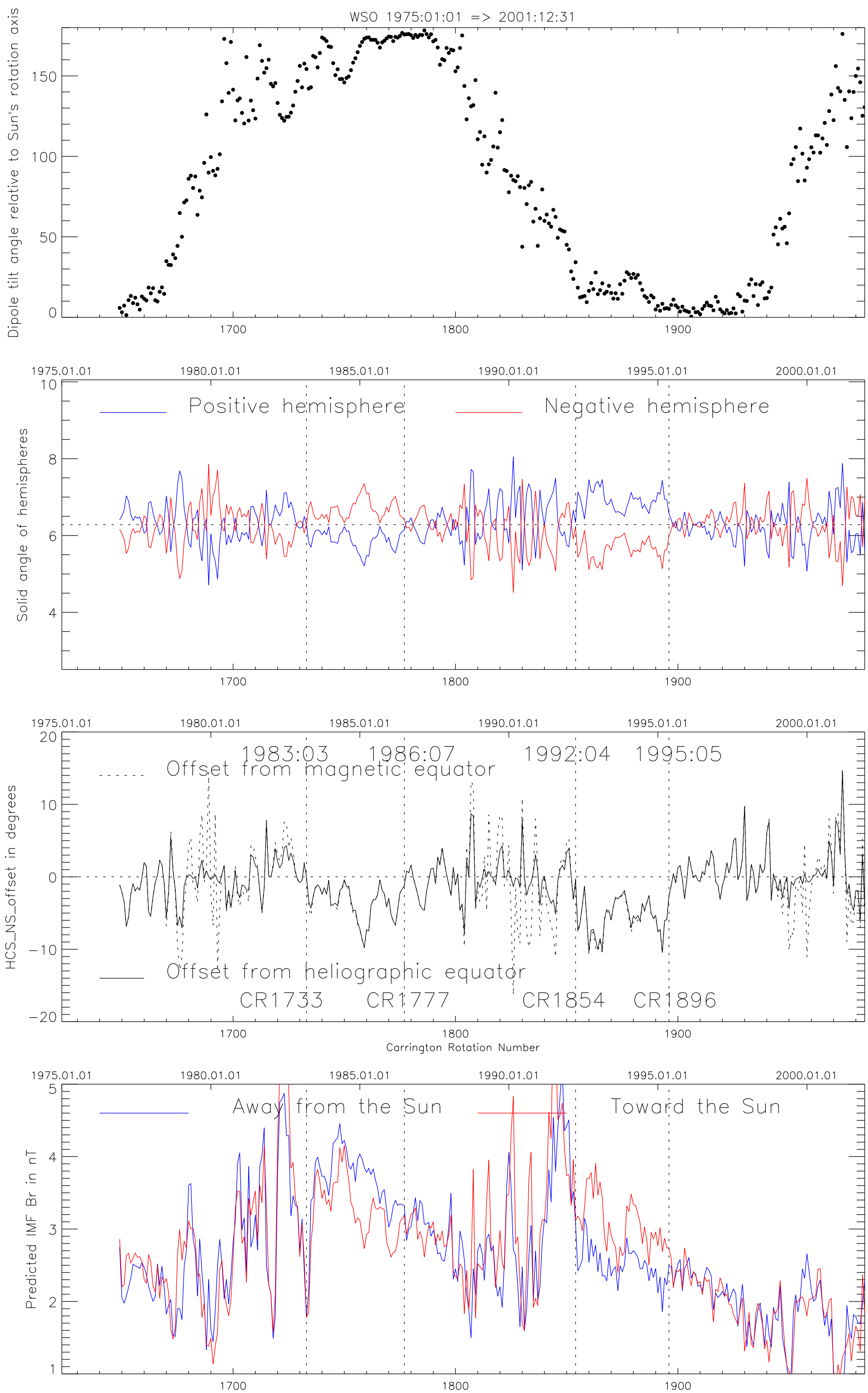

Fig. 2.— The dipole tilt angle (the top panel), the solid angle of positive and negative magnetic hemispheres (the second panel), the offset of the HCS from heliographic (magnetic) equator (the third panel), and the asymmetry of field strength between two hemispheres from 1976 to 2001.

4. The cause of the north-south asymmetry of HCS

The north-south asymmetry in the global heliosphere around sunspot minimum has been suggested to be caused by the north-south asymmetry in Sun's polar magnetic field [Jokipii and Smith, 1998]. The photospheric magnetic field can be expanded as multipoles, and the heliospheric magnetic field is contributed mainly by the dipole, the hexapole, and the quadrupole, in that order. Around sunspot minimum, the dipole, the hexapole, and the quadrupole are oriented basically parallel to the Sun's rotation axis, can be approximately represented by g_{10}, g_{30} and g_{20}. The polar field produced by g_{10} and g_{30} has opposite polarity in north and south polar regions, but the polar field produced by g_{20} has same polarity in both polar regions. The north-south asymmetry in the heliosphere around sunspot minimum is thus produced by the existence of a significant quadrupole term, g_{20}, in the global magnetic field of the Sun [*Bravo and Gonzalez-Esparza*, 2000]. The magnetic field is thus greater (less) in the south polar region than in the north if g_{10} and g_{20} have opposite (identical) sign. The HCS is displaced southward (northward) from the equator when g_{10} and g_{20} have opposite (identical) sign if there are no other factors affecting the north-south asymmetry.

Figure 3 displays the mean radial field over polar regions (the top panel), the rotation-axis aligned dipole and quadrupole, g_{10} and g_{20}, in the middle panel, and the offset of the HCS from Sun's equator in the bottom panel. Figure 3 shows that during the two intervals of long southward displacement of the HCS, the mean polar radial field is greater in the south than in the north, and the dipole and quadrupole are mostly in opposite orientation. There are at least two rotations between March 1983 and July 1986 when the dipole and quadrupole have same orientation but the HCS is displaced still southward, suggesting there are other factors that may affect the north-south asymmetry of the heliosphere.

Figures 4a and 4b displays 20 synoptic maps for 20 years. Each represents one year. It is shown that for Carrington rotations around sunspot maximum the north-south offset is certainly not determined only by the sign of g_{10} and g_{20}.

Figure 5a shows the case of no offset of the HCS, though the area and mean field strength in the north and south open field regions are not symmetric, suggesting that in addition to the area (or the mean field strength because of the balance between positive and negative magnetic fluxes), there are other factors that affect the north-south asymmetry. Figure 5b shows a northward displacement of the HCS, though g_{10} and g_{20} have opposite sign. The top panels in Figures 5a and 5b show the existence of low latitude open field regions that has no association with the polar field.

The displacement of the HCS for CR1893 southward from the magnetic equator implies that the surface area occupied by the positive source surface field, A_{ss}^{N}, is greater than the surface area occupied by the negative source surface field, A_{ss}^{S}. Here

$$A_{ss}^{NS} = \epsilon^{NS} A_{fp}^{NS} \left(\frac{R_{ss}}{R_{\odot}}\right)^2 \tag{11}$$

where ϵ^{NS} is the mean expansion factor of the north or south open field regions between $R_{\odot}$ and R_{ss} and defined as

$$\epsilon^{NS} = \frac{\overline{B_{fp}^{NS}}}{\overline{B_{ss}^{NS}}} \left(\frac{R_{\odot}}{R_{ss}}\right)^2, \tag{12}$$

and A_{fp}^{NS} is total foot point area of open field lines in the north or south magnetic hemisphere,

$$A_{fp}^{NS} = \sum_{i}^{I^{NS}} \delta A_{fpi}^{NS} \tag{13}$$

The mean foot-point field in Equation (12),

$$\overline{B_{fp}^{NS}} = \frac{\sum_i^{I^{NS}} B_{fpi}^{NS} \delta A_{fpi}^{NS}}{A_{fp}^{NS}} \tag{14}$$

where the elemental foot-point area in Equations (13) and (14)

$$\delta A_{fpi}^{NS} = \frac{B_{ssi}^{NS}}{B_{fpi}^{NS}} \delta A_{ssi}. \tag{15}$$

Here $\delta A_{ssi} = R_{ss}^2 \delta\Omega_{ss}$ is the elemental source surface area, B_{fpi}^{NS} is the foot-point field strength connecting to the source surface field strength B_{ssi}^{NS}.

Figure 7 displays the mean field, $\overline{B_{fp}^{NS}}$, total area, A_{fp}^{NS}, and mean expansion rate (between solar surface and source surface), ϵ^{NS} of positive and negative open field regions, and the total area of positive (negative) source surface field, A_{ss}^{NS} obtained from Equation (7). As shown in Equation (11), it is the difference in total foot-point areas, A_{fp}^{NS} and their mean expansion factor, ϵ^{NS}, between north and south open field regions that determines the difference between A_{ss}^{N} and A_{ss}^{S}, or the north-south asymmetry in the global heliosphere. Only around sunspot minimum when there is no low latitude open field regions, the asymmetry of the polar field determines the asymmetry in the global heliosphere.

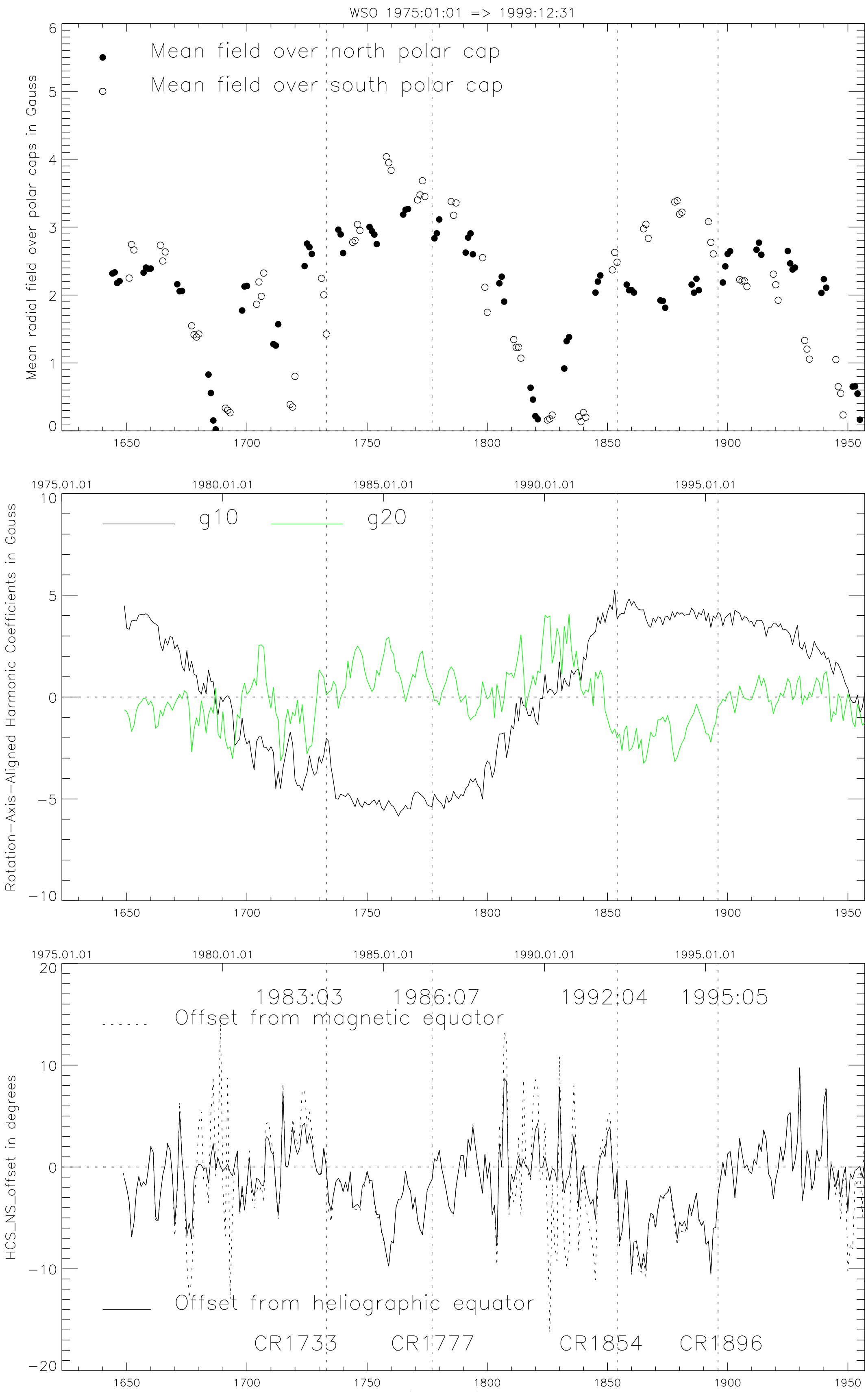

Fig. 3.— The association of north-south offset of the HCS (the bottom panel) with the WSO mean polar filed (the top panel) and the rotation-axis-aligned dipole and quadrupole, g10 and g20 (the middle panel).

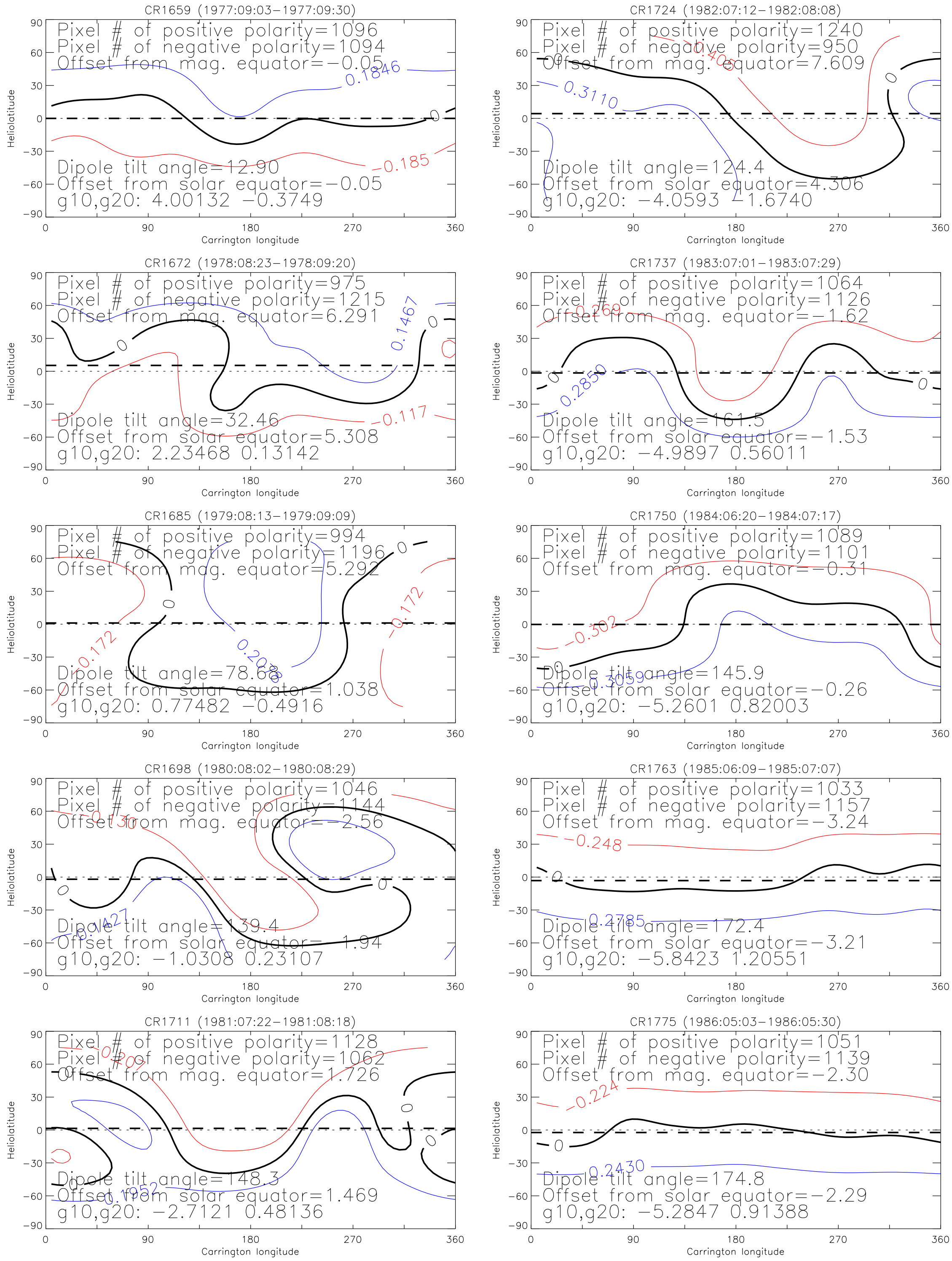

Fig. 4a.— The neutral line (solid dark line) and its offset (dashed dark line) from the heliomagnetic equatorial plane (dotted line) computed between 1997 and 1986.

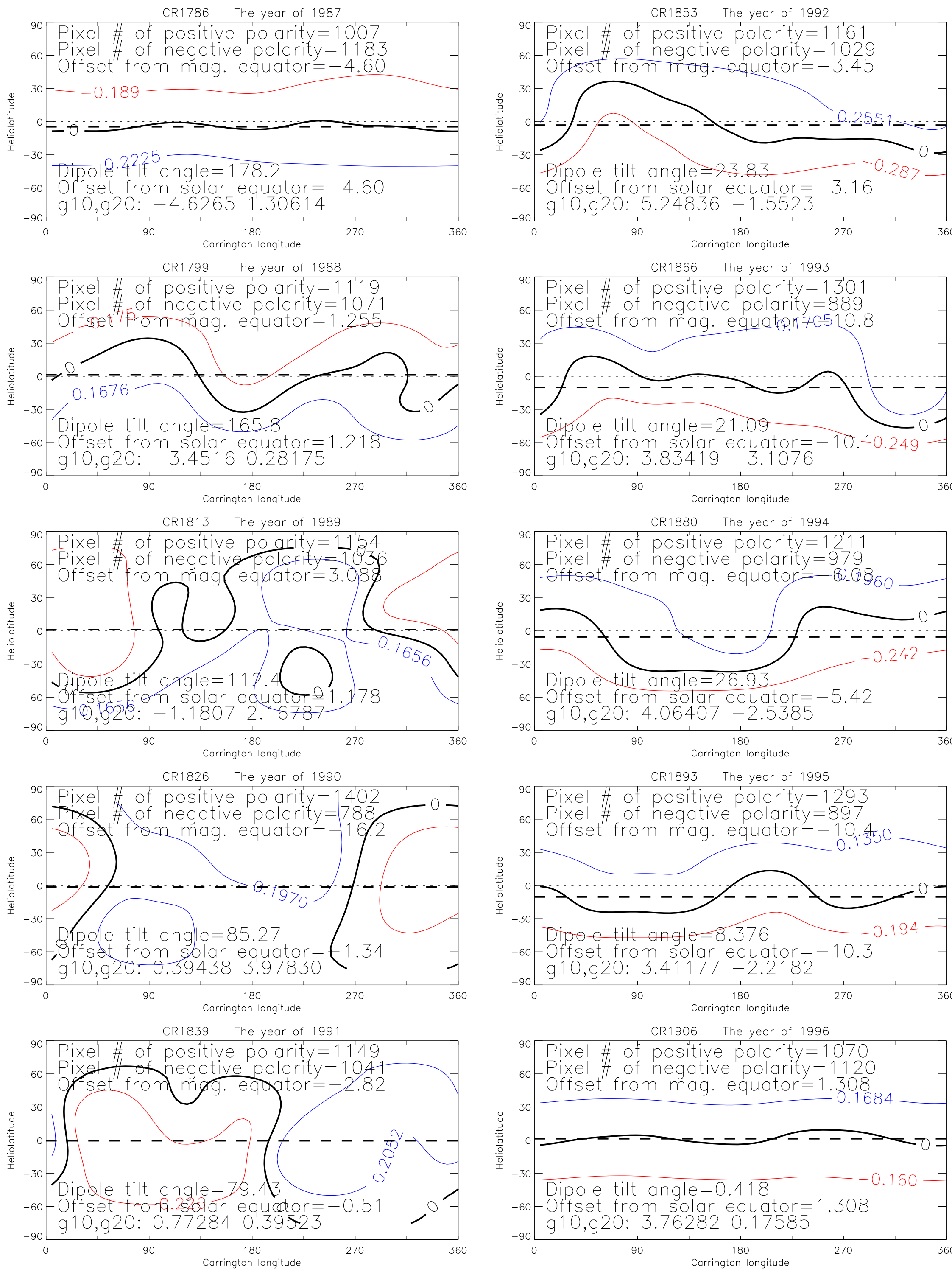

Fig. 4b.— The neutral line (solid dark line) and its offset (dashed dark line) from the heliomagnetic equatorial plane (dotted line) computed between 1987 and 1996.

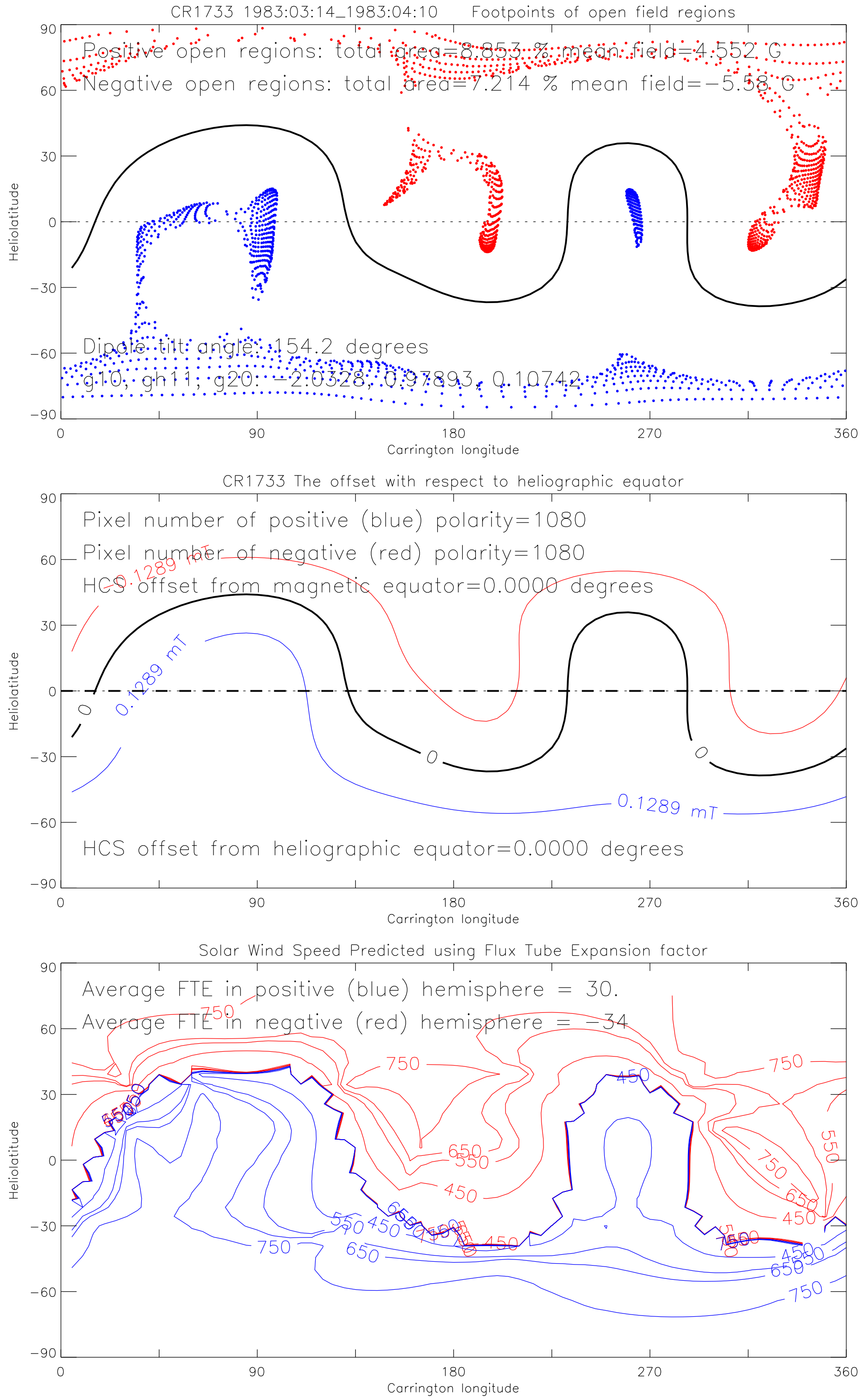

Fig. 5a.— The positive (blue) and negative (red) open field regions (the top panel), the neutral line and its ZERO offset from the equator (the middle panel), and the flux tube expansion factor (the bottom panel) for Carrington rotation 1733.

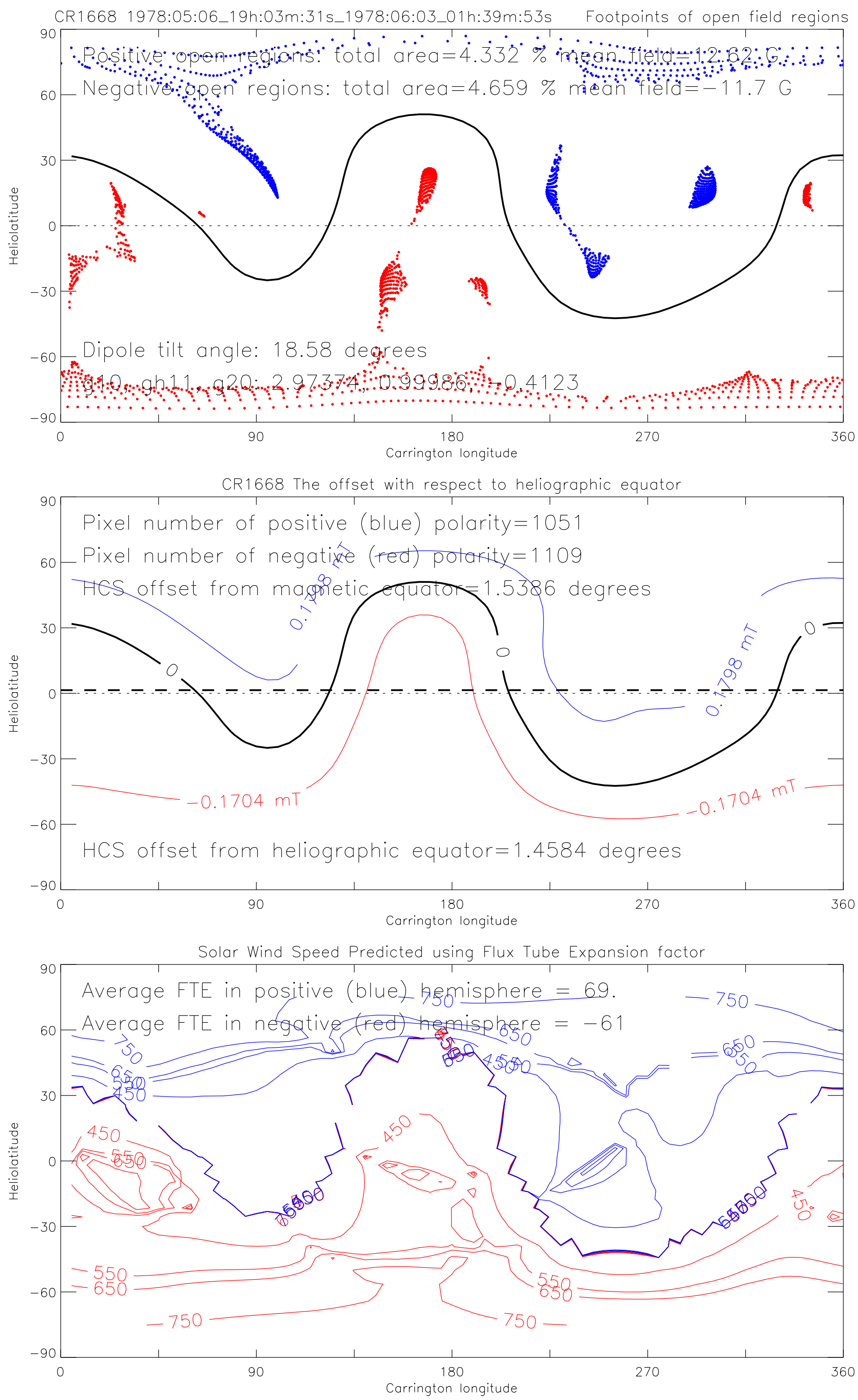

Fig. 5b.— The same as Figure 6b but for Carrington rotation of 1668 when the offset of the HCS is northward, though the dipole and quadrupole are pointed oppositely.

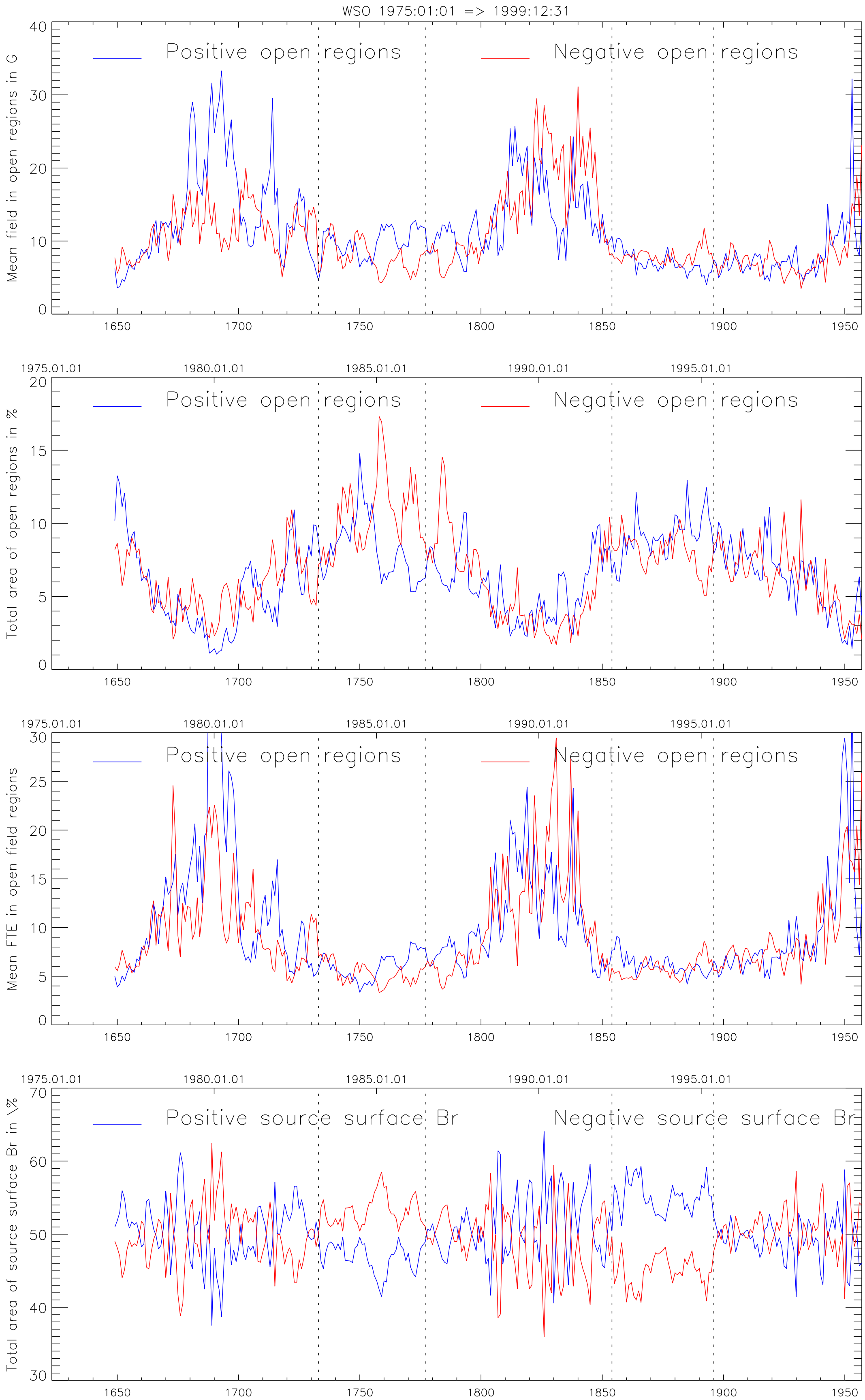

Fig. 6.— The mean field and total area of positive and negative open field regions, and the mean expansion rate of open field regions between solar surface and source surface, and the pixel number of positive and negative source surface field.

5. Summary and discussion

• We develop a method to estimate the north-south asymmetry in the global heliospheric magnetic field. The computed southward offset of the HCS for Carrington rotation 1893 and the ratio of mean source surface field between two hemispheres agree very well with the inferences from the measurements made at Ulysses and WIND spacecraft (Simon, 1976; Smith et al., 2000).

• The north-south offset of the HCS computed over 25 years shows that the north-south offset of several degrees occurs frequently and alternatively. Each offset lasts for a few solar rotations.

• There are two long intervals before and near the sunspot minimum of solar cycles 22 and 23 when the SOUTHWARD offset of the HCS lasts more than three years. A configuration in which the HCS is displaced southward, leading to the disappearance of the sector structure in the ecliptic near sunspot minimum, was reported many years ago (Wilcox, Comments on Astrophys. and Space Phys., 4, 141, 1972), suggesting that the SOUTHWARD offset of the HCS near sunspot minimum appears to be an intrinsic phenomenon.

• The north-south offset of the HCS from solar equator depends on the asymmetry between north and south magnetic hemispheres in the surface area of open field regions and its expansion rate from coronal base to the source surface It depends also on the Sun's dipole tilt angle. Around sunspot minimum, the Sun's dipole basically parallel to Sun's rotation axis, and there is no significant difference in expansion rate between north and south polar holes, the offset depends mainly on the asymmetry in the area or field strength between north and south polar coronal holes.