JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. A1, 1035, doi:10.1029/2002JA009388, 2003

Observations of the Sun's magnetic field during the recent solar maximum

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Received 15 March 2002; revised 24 September 2002; accepted 27 September 2002; published 24 January 2003.

[1] We present new observations and analyses of the Sun's magnetic field and coronal holes. Using magnetic field observations from the Wilcox Solar Observatory, we present a simple means whereby the tilt angle of the current sheet can be calculated. We use a data set covering the last 26 years, which shows for the first time how the dipole component rotated once during a full 22-year solar cycle. We show how this influenced the current sheet. At solar minimum, the Sun's coronal magnetic field was essentially dipolar and aligned parallel to the spin axis. As a result, the heliospheric current sheet was flat and had very little warp. Around solar maximum, the dipole was perpendicular to the spin axis, and the ratio of quadrupole to dipole strength was high for much of the time. This meant that the current sheet was tilted and highly warped, and reached up to high latitudes. Surprisingly, there were also times close to solar maximum when the quadrupole/dipole ratio was low, and the current sheet was relatively flat, but still highly inclined. We apply for the first time to solar magnetic data a method, which quantitatively analyses the quadrupole component of the magnetic field. From the terms of the expansion of the observed photospheric magnetic field, we compute the position of the poles of the magnetic field. We combine for the first time over an extended period of time magnetic field data from the Wilcox Solar Observatory with coronal hole positions taken from the National Solar Observatory/Kitt Peak. We find that the position of the coronal holes followed the motion of the poles of the magnetic field as the poles moved over the surface of the Sun and that the polar coronal holes broke up into groups of smaller like-polarity holes as the poles approached the midlatitude regions and the quadrupole became more important. We discuss the implications for energetic particle observations at Ulysses. *INDEX TERMS:* 7509 Solar Physics, Astrophysics, and Astronomy: Corona; 7511 Solar Physics, Astrophysics, and Astronomy: Coronal holes; 7524 Solar Physics, Astrophysics, and Astronomy: Magnetic fields; 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles (2114); *KEYWORDS:* current sheet, source surface, Sun's dipole, Sun's quadrupole, coronal holes, solar maximum

Citation: Sanderson, T. R., T. Appourchaux, J. T. Hoeksema, and K. L. Harvey, Observations of the Sun's magnetic field during the recent solar maximum, *J. Geophys. Res.*, *108*(A1), 1035, doi:10.1029/2002JA009388, 2003.

1. Introduction

[2] The evolution of the Sun's magnetic field and the coronal neutral sheet, and their influence on the interplanetary medium, have been the subject of continual attention for at least the last two solar cycles. Likewise, coronal holes, known for some time as the source of high-speed solar wind flow, have been the subject of continual study ever since their discovery in the late 1950s [see for example, *Zirker*, 1977]. The interaction of this high-speed flow with the lower speed flow from the streamer belt [e.g., *Barnes and Simpson*, 1976] gives rise to co-rotating interaction regions (CIR). This topic has taken on a new importance with the discovery by Ulysses of the existence of these CIRs at high latitudes [*Sanderson et al.*, 1994; *Simnett et al.*, 1994].

[3] Measurements on the IMP-1 spacecraft as early as 1965 [*Wilcox and Ness*, 1965] had shown the existence of magnetic sectors of opposite polarity in the interplanetary magnetic field at 1 AU. To explain this, *Altschuler and Newkirk* [1969] and *Schatten et al.* [1969] used a mathematical model of a spherical source surface and a radially emanating field, with a neutral line separating the two hemispheres and used it to compute the interplanetary magnetic field sector boundaries. In 1973, *Schulz* [1973] suggested that these magnetic sectors were the result of multiple crossings of the large-scale heliospheric current sheet separating two opposite magnetic hemispheres of the Sun. The two-sector patterns were the result of a tilted solar magnetic dipole, and

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0148-0227/03/2002JA009388$09.00

the four-sector patterns were the result of an additional warp due to a quadrupole contribution to the current sheet.

[4] By this time, coronal holes were thought to be fairly large, cool, low-density areas, which lay within large-scale unipolar areas of the Sun. They were observed both at low latitudes and at the poles and gave rise to high-speed solar wind flow. The Skylab observations [*Zirker*, 1977] added substantially to this understanding.

[5] Since then, there have been numerous attempts to relate magnetic field measurements on the Sun to observations at 1 AU. Of relevance here are the early works describing solar minimum 2 solar cycles ago, e.g., *Burlaga et al.* [1981] and *Hoeksema et al.* [1982, 1983], which established and quantified many of the ideas presented in this paper. These authors, using either K-Coronameter or solar magnetograph measurements, found that at solar minimum the tilt of the dipole is small, typically only a few degrees, and that small warps of only a few degrees can be as significant as the tilt.

[6] In the period around solar minimum two solar cycles ago [*Hoeksema et al.*, 1982], the warp and the tilt were such that two northward and two southward extensions of the current sheet were observed, giving rise to a four-sector structure at 1 AU. The general trend was that of a slow evolution of features affecting the current sheet with a time-scale of several months, different features drifting slowly either eastward or westward relative to the coronal rotation, similar to the observations which we will present here.

[7] Recent work on the properties of coronal holes include extensive analyses and modeling of the long-term evolution of coronal holes [*Wang et al.*, 1996; *Luhmann et al.*, 2002], and of the Sun's open magnetic flux [*Neugebauer et al.*, 2003; *Wang and Sheeley*, 2002].

[8] In recent years, the high-latitude Ulysses mission has enabled us to look at the interaction regions caused by a tilted current sheet [*Sanderson et al.*, 2001; *Smith et al.*, 2001] and their effect on energetic particles. In *Sanderson et al.* [2001], we combined Ulysses data with the model of the neutral line based on observations at the Sun by the Wilcox Solar Observatory and with observations of the position of the coronal holes, and showed how changes, mapped out to the position of the spacecraft, influenced the recurrence of the interaction regions, which in turn, controlled the energetic particle increases observed at Ulysses.

[9] In this paper, we examine in more detail the Sun's magnetic field and coronal holes. We examine the dipolar and quadrupolar terms in the computed expansion of the coronal magnetic field during the recent solar maximum. These are the dominant components determining the shape of the heliospheric current sheet in the upper corona and heliosphere. Higher order terms only become important closer to the Sun.

[10] We show how the dipole rotated once during the 22-year solar cycle, and how the quadrupole term reached a maximum around the time of solar maximum. We discuss how this determined the tilt and the warps of the model current sheet during the recent solar maximum. Warps due to active regions changed on a timescale of several solar rotations whereas changes in the dipole axis direction took place on a timescale of the solar cycle.

[11] We show how the ratio of quadrupole to dipole strength varied during the recent Ulysses fast latitude scan. We combine this with data showing the boundaries of the coronal holes as observed by the National Solar Observatory/Kitt Peak spectromagnetograph, and show how the coronal holes followed the high-field regions (the dipole and quadrupole poles) as they tracked across the Sun's disc during the course of the solar cycle, how their shape evolved, and how this influenced the three-dimensional heliosphere.

2. Observations and Discussion

[12] The observations of the Sun's magnetic field and coronal holes presented here were made by the Wilcox Solar Observatory (WSO) and the National Solar Observatory/Kitt Peak, respectively. Daily large-scale photospheric magnetic field measurements are made by the Wilcox Solar Observatory, from which the coronal field can be calculated using a Potential Field Source Surface model. A complete description of the method used to derive the parameters with which to describe the Sun's coronal field can be found in *Hoeksema* [1984] and on the WSO web site under http://quake.stanford.edu/~wso/Description.ps.

[13] Here we use the WSO 9-order potential field model classical fit with a source surface at 2.5 Rs to compute the coronal magnetic field [*Hoeksema*, 1984]. According to the WSO web site, http://quake.stanford.edu/~wso/coronal.html, the 2.5 solar radii source surface gives the best overall agreement with the polarity pattern observed at Earth. We use the coefficients of the multipole expansion stored on the WSO home page http://www.wso.edu to generate magnetic field contours and so determine the positions of the magnetic poles. The contour of zero magnetic field strength is the position at the Sun of the source surface neutral line. When propagated outwards with the solar wind speed, this can be used as a proxy for the position of the heliospheric current sheet, with reasonable accuracy up to 1 or 2 AU, as demonstrated, for example, by *Suess and Hildner* [1985], *Roelof et al.* [1997], *Neugebauer et al.* [1998, 2003], and *Sanderson et al.* [1999].

[14] Coronal hole data are taken from the National Solar Observatory/Kitt Peak spectromagnetograph [*Jones et al.*, 1992]. Here we use boundaries of the coronal holes derived by NSO/Kitt Peak from images taken in the He I 1083 nm line by the NSO/Kitt Peak instrument.

3. The Dipole Terms

[15] Figure 1, which covers a period of 26 years starting in 1976, shows for the first time how the zero-order and first-order terms of the photospheric magnetic field varied over a full 22-year solar cycle. We show, in the bottom panel, the zero-order term g_{00}. This monopole term results from limitations of the solar observations, i.e., visibility, viewing angle, temporal variations, noise etc. The next two panels show the three first-order (dipole) coefficients, g_{10}, g_{11}, and h_{11}.

[16] We can visualize the first order using *Maxwell*'s [1891] theory of spherical harmonic poles. The first order can be described by an amplitude δ_1 and a harmonic 'pole' direction θ_1 and ϕ_1. According to *Maxwell* [1891], the value of the first-order surface harmonic, Y_1, at any position is given simply by

$$Y_1 = \mu_1$$

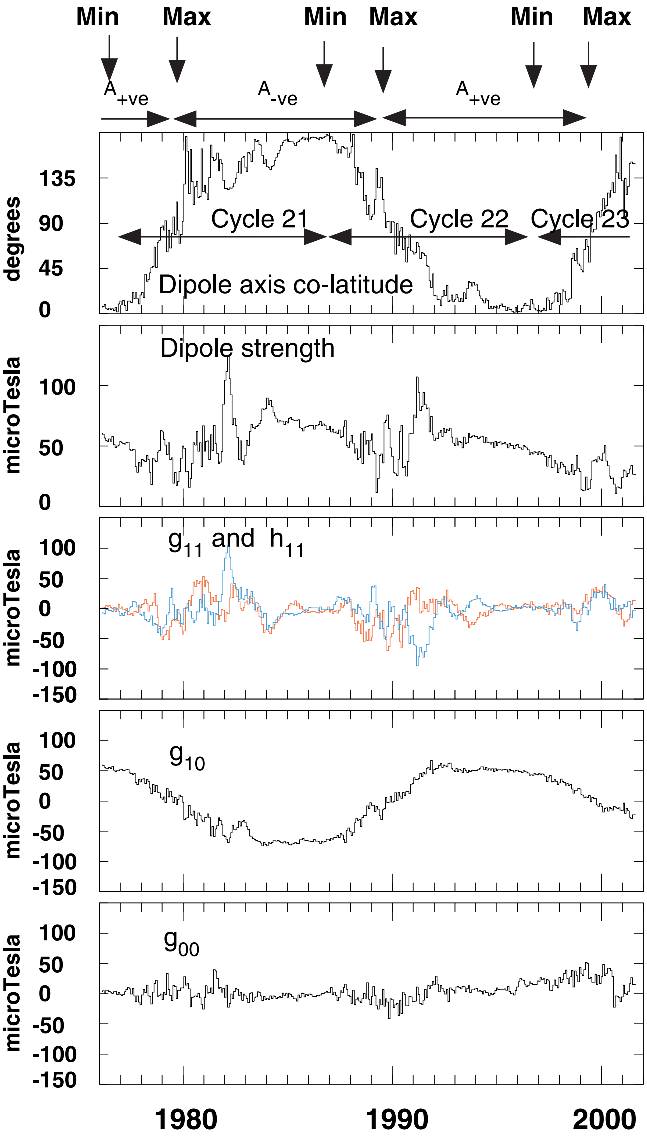

Figure 1. The Sun's dipole terms from 1976 to 2001 as derived by the Wilcox Solar Observatory. This shows the zero-order term g_{00}, the first-order axial component g_{10}, and the two first-order azimuthal components, g_{11} and h_{11}. The top two panels show the first-order magnitude (the dipole strength) and the direction θ_1 (the co-latitude of the dipole axis) derived using Maxwell's theory of poles.

where μ_1 is the cosine of the angle between the position and the harmonic 'pole' direction θ_1 and ϕ_1.

[17] The polar angle, or co-latitude, of the first-order harmonic 'pole' is given by $\theta_1 = \arccos\,(g_{10}/\delta_1)$. The amplitude δ_1 of the first order is the dipole strength. The direction of the first-order harmonic 'pole' corresponds to direction of the north magnetic dipole pole and so the angle θ_1 is the angle between the north magnetic dipole pole and the spin axis of the Sun.

[18] In Figure 1, we show, in the top two panels the dipole strength, δ_1, and the co-latitude, θ_1, of the magnetic dipole pole derived from the first-order axial and azimuthal terms (second and third panels). In one complete 22-year solar cycle, the axis of the dipole rotated from pointing north (0°) at the start of Cycle 21 (solar minimum, 1976), to pointing south (180°) at the start of Cycle 22 (solar minimum again) and back to pointing north (0°) at the start of Cycle 23 (solar minimum again, 1996). At the minimum during the positive 11-year cycle, the axis was parallel, and at the minimum during the negative 11-year cycle, it was antiparallel to the Sun's spin axis. At the maximum of a cycle, the dipole was perpendicular to the spin axis. Note that the magnitude of the dipole is much smaller at each solar maximum.

[19] If the field consists only of a dipole term, then the extension of the neutral line into the heliosphere, the current sheet, will be a flat plane with the normal to the plane inclined with respect to the Sun's heliographic z axis. The tilt of the current sheet depends on the orientation of the dipole, and the tilt angle of the normal to the current sheet is same as the co-latitude of the axis of the dipole. The normal to the current sheet slowly tilts away from the Sun's spin axis as the dipole axis tilts away from the Sun's spin axis.

4. The Quadrupole Terms

[20] In Figure 2, we show for the first time how the second-order term, the quadrupole, varied during the 12-year period starting in 1990. The bottom three panels show the five second-order coefficients, g_{20}, g_{21}, h_{21}, g_{22}, and h_{22}. Using *Maxwell*'s [1891] theory of spherical harmonic poles again, we can visualize the second-order terms as an amplitude δ_2 and two harmonic 'pole' directions θ_{21}, φ_{21} and θ_{22}, φ_{22}. According to *Maxwell* [1891], the value of the second-order surface harmonic, Y_2, at any position is given simply by

$$Y_2 = 3/2\mu_{21}\mu_{22} - 1/2\lambda_{12}$$

where μ_{21} is the cosine of the angle between the position and the harmonic 'pole' direction θ_{21} and ϕ_{21}, μ_{22} is the cosine of the angle between the position and the direction θ_{22} and ϕ_{22} and λ_{12} is the angle between the two harmonic 'poles'.

[21] The second-order amplitude and the directions θ_{21} and ϕ_{21} and θ_{22} and ϕ_{22} can be calculated using the method of *Umow* [1904]. The amplitude δ_2 is the quadrupole strength. If the direction of the harmonic 'pole' θ_{21} and ϕ_{21} is **B**, and the direction of the harmonic 'pole' θ_{22} and ϕ_{22} is **C**, then the directions of the magnetic quadrupole poles are **B**−**C** or **B** + **C**.

[22] In Figure 2 we show, in the top three panels the amplitude of the quadrupole strength, δ_2 and the directions of the magnetic quadrupole poles as derived above. Plotted are the polar angles of one of the positive and one of the negative magnetic quadrupole poles. These directions correspond to two of the four magnetic quadrupole maxima and minima.

[23] In this plot, the quadrupole strength decreased to a minimum in 1996, around the time of solar minimum. It rose again early in 1998, reaching a maximum in late 1999, around the time of maximum of Cycle 23.

[24] Around solar maximum, the field was dominated by the two sectoral quadrupolar terms g_{22}, and h_{22}, which shows that maximum or minimum of the field lies in the equatorial plane. When the field is dominated by the sectoral quadrupolar field, the locus of the current sheet approximates to a sinusoidal curve when plotted versus Carrington longitude, but with a period equal to one half of a rotation. At other times, the dipole and quadrupole terms were present in similar amounts, and the current sheet was

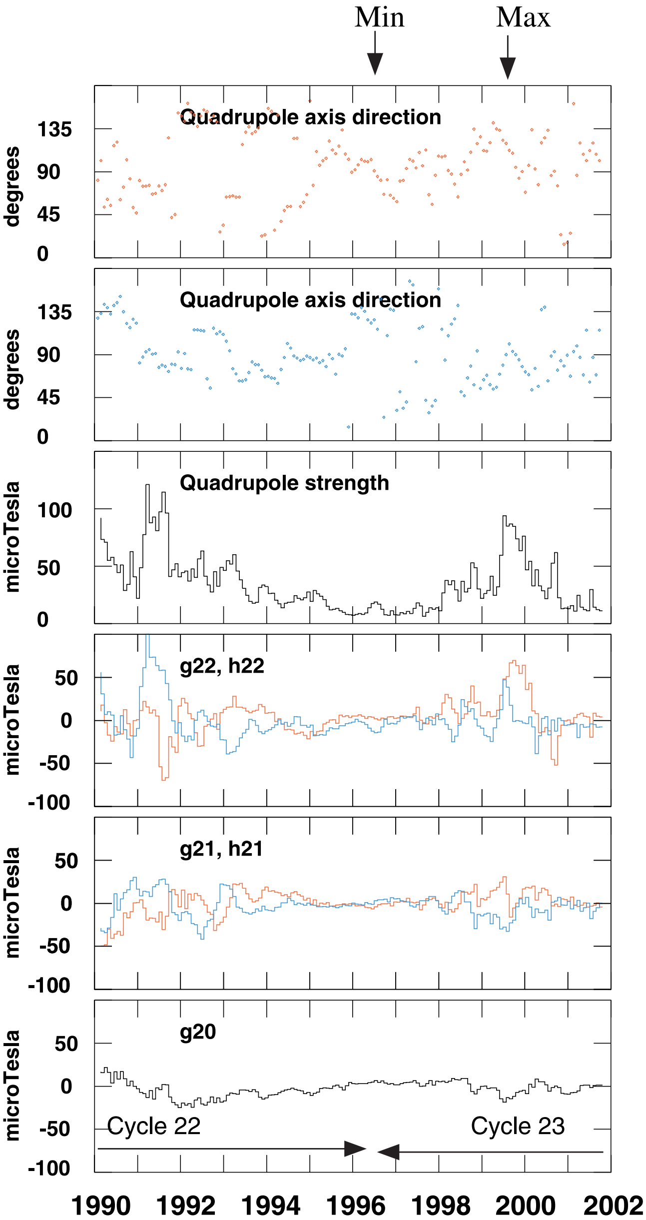

Figure 2. The Sun's quadrupole terms from 1990 to 2001 as derived by the Wilcox Solar Observatory. The bottom three panels show the second-order axial term g_{20}, the second-order tesseral terms g_{21} and h_{21} and the second-order sectoral terms g_{22} and h_{22}. The top three panels show the second-order magnitude (the quadrupole strength) and directions θ_{21} and θ_{22} (the co-latitude of one of the positive and one of the negative magnetic poles) derived using Maxwell's theory of poles.

both tilted and warped. The dipole term determines the tilt of the current sheet, whereas the quadrupole term determines the warp [*Schulz*, 1973].

[25] The directions plotted in the top panel are the positive and negative 'poles' of the quadrupole. These 'poles' moved around on the surface of the Sun, but were located mainly at low and midlatitudes.

[26] The axial term, g_{20}, is shown in the bottom panel. This term is normally close to zero. This term was negative during the period 1991–1996 and again in 1999, and is indicative of a slight asymmetry in the polar fields.

5. Solar Cycle 23 Examples

[27] In Figure 3a, we show six examples of WSO source surface field maps for Carrington Rotations 1925, 1935, 1945, 1955, 1965, and 1975, (every tenth rotation), which cover the period from July 1997 to April 2001. Here we show the model field plotted with a Mercator projection. Each plot shows the contours of the Sun's source surface magnetic field at 2.5 Rs with superimposed on it the location of the boundaries of the coronal holes. Positive fields are blue, and negative fields are red. The steps in the shading range from -30 to $+30$ μT. The contours and shading do not extend all the way to the poles since the Sun's polar field is not well determined due to the difficulties in measuring the line of sight component of the radial field near the limb of the photosphere. These plots are derived from the coefficients posted on the WSO web site and are similar to the source surface maps on the same site. Additional shading included here shows the regions of high field strength (the positions of the maxima and minima of the field) which suggests that these are the positions of the poles of the magnetic field at the source surface.

[28] The calculated position of the dipole and quadrupole poles are shown by the colored circles. The large blue circle is the position of the positive dipole pole, the large red circle is the position of the negative dipole pole, the two small blue circles are the positions of the positive quadrupole poles, and the two small red circles are the positions of the two negative quadrupole poles.

[29] The positions of the outlines of the coronal holes are plotted on top of the magnetic field contours, again with blue signifying positive, and red signifying negative polarity. Superimposed on top, in black, is the position of the neutral line, or current sheet.

[30] In Figure 3b we show the same six Carrington Rotations, but now plotted with an orthographic projection. This projection has the advantage that it shows the sphere as seen from infinity, but has the disadvantage that only one hemisphere can be seen. Here we show this sphere viewed from four different directions, namely, from the north, south, east and west directions (heliographic coordinates). Again, these plots show the contours of the magnetic field strength, with superimposed upon them the positions of the coronal holes, the neutral line and the pole positions.

[31] The plots in Figures 3a and 3b show how the computed magnetic field changes during the five years around solar maximum, and shows the transition from, at the top, Panel 1, an almost flat equatorial current sheet, through Panels 2 and 3 which show a mixed quadrupolar/dipolar field, Panel 4 a quadrupolar field, to Panels 5 and 6, a tilted dipolar field. This shows how the poles of the magnetic field move across disk, and changed from a dipolar to quadrupolar field, how the current sheet evolved, and how coronal holes followed the poles of the magnetic field.

[32] Figures 3a and 3b, Panel 1, show the situation for Carrington Rotation 1925, which was centered on 29 July 1997. This is typical of the period around solar minimum. The field then was dipolar, with the dipole axis aligned with

the Sun's spin axis. The almost straight contour lines in Figure 3a mean that the contours of equal magnetic field are almost circular, and centered on the heliographic poles, as can be seen in Figure 3b. This means that the magnetic poles coincided with the north and south heliographic poles of the Sun. The current sheet was nearly flat and in the equatorial plane. There was one large positive coronal hole (blue) located at the positive magnetic pole (the North heliographic pole) and one negative hole (red) at the negative magnetic pole (the South heliographic pole). The edges of these holes, although rather ragged, are more or less concentric with the magnetic potential contours. Each polar coronal hole had an equatorial extension. Just a few midlatitude coronal holes were present.

[33] The next example, Panel 2 (28 April 1998, CR 1935), is typical of the rise to solar maximum, as the inclination of the dipole with respect to the spin axis increased. The contours of the magnetic field as seen from the north and the south had started to elongate as the dipole tilt increased and the quadrupole strength increased. Near the equator, two maxima and two minima in the colored contours were present, which means that the quadrupoles were beginning to appear. The field had changed to a mixed quadrupolar/dipolar form with the quadrupole structure being more dominant. The current sheet was similar to the line separating the two halves of a tennis ball. The polar coronal holes were smaller, and the edges of the polar coronal holes had started to elongate and follow the elongation of the poles, and were giving the impression of starting to break up. This gives the impression that the midlatitude coronal holes had sheared off from the polar holes, probably due to differential rotation, as the poles elongate. The midlatitude holes were clustered around the magnetic multipoles.

[34] In the third example, Panel 3, from early 1999 (25 January, 1999, CR 1945), the field was again mixed dipolar/quadrupolar, but this time the dipole was more dominant. The dipole was tilted significantly away from the Sun's rotation axis. The current sheet was tilted due to the tilt of the dipole, and was warped due to the quadrupolar component. The polar coronal holes had elongated even more, and midlatitude holes gave the impression that they had sheared off from the polar coronal holes. The midlatitude coronal holes were clustered around the magnetic multipoles.

[35] Later in 1999, Panel 4, around the time of solar maximum, (CR1955, 25 October 1999), the field had become quadrupolar and the dipole field was very weak, typical of the period around solar maximum. The two positive poles (blue maxima) and the two negative poles (red minima) of the field, the result of a dominant quadrupole, were clearly visible at midlatitudes. The current sheet threaded its way around the quadrupole poles and an additional current sheet had appeared around one pole. This situation lasted only for one or two rotations. The polar coronal holes had shrunk considerably, and there was a large midlatitude extension from the negative coronal hole. Midlatitude coronal holes were clustered around the four quadrupole poles.

[36] In 2000, Panel 5, just after the time of solar maximum (CR1965, 24 July 2000), the field was again dipolar and the quadrupolar term was small. This configuration was somewhat unexpected. The dipole axis was inclined at around 90° to the spin axis, giving rise to a more or less flat, but highly tilted current sheet. The current sheet extended to high heliographic latitudes and almost crossed over the heliographic poles. The polar coronal holes had disappeared, and midlatitude coronal holes were clustered around the contours of high magnetic field strength. This time corresponded to the time Ulysses was nearly at its maximum southern latitude. No southern polar coronal hole was observed. At this time, the south pole was tipped away from the Earth. This made it difficult to confirm the Ulysses observation that the southern pole had not yet reversed, although the fit to the magnetic field data, based on observations which do not spatially resolve the field above 55°, showed otherwise.

[37] In 2001, Panel 6, 23 April 2001, well after solar maximum, the field was dipolar, but still tilted with respect to the Sun's rotation axis. The dipole poles were at midlatitude, and the current sheet was inclined, but relatively flat. Midlatitude coronal holes were clustered around the two high-field regions, and a midlatitude coronal hole in the northern hemisphere appeared to be forming into a polar coronal hole. The polar coronal hole at the northern pole was of the opposite polarity to that shown in Panels 1–4, signifying that the polarity of the northern pole was reversed. The actual time of reversal was probably halfway between this time and the time of disappearance of the positive northern coronal hole in early 2000.

6. Solar Cycle 23 Synopsis

[38] In Figure 4, we show an extended synoptic plot made up of 66 Carrington Rotations of model coronal field and coronal hole data for the 5-year period up to and around the Ulysses second fast latitude scan, using the data shown in Figure 3.

[39] In the Panel 1 we show the calculated latitude of the current sheet at the Sun's central meridian versus time, with the heliographic latitude of the Ulysses spacecraft superimposed upon it. In Panels 2 and 3, we show the position of the positive polar and equatorial coronal holes, and the positions of the negative polar and equatorial coronal holes, respectively. In Panels 4 and 5, we show contours of equal positive and negative magnetic field strength, respectively, which represent the suggested positions of the magnetic poles. The value of the contours are at plus and minus 5 μT. The data gap in Panels 4 and 5 early in 2001 is due to calibration problems, which resulted in a reduced sensitivity of the WSO instrument. Panel 6 shows the ratio of the quadrupole strength to dipole strength.

[40] We have divided these 5 years into several distinct periods, as shown in Panel 6 on the basis of the ratio of quadrupole to dipole strength. In Period 1, the field was predominantly dipolar, with the dipole axis approximately parallel to the Sun's spin axis. In Period 2, just before solar maximum, the field was a mixture of dipolar and quadrupolar structures. In Period 3, the field was dipolar again, and was followed by Period 4 when it was mainly quadrupolar, around the time of solar maximum. Thereafter, there were four short periods (5, 6, 7, and 8) when the field became dipolar, quadrupolar, mixed, and then dipolar again.

[41] Panels 4 and 5 show the motion of the poles of the magnetic field as they track across the disc of the Sun during the change from solar minimum to solar maximum. In 1997, the positive and negative contours show that

1. Dipolar field. **CR 1925. 29 July 1977.**
Field dipolar with axis along Sun's rotation axis
Poles of dipolar coincide with N and S pole
Current sheet almost flat
Polar coronal holes almost circular with small equatorial extension
Mid-latitude coronal holes virtually non-existent

2. Mixed quadrupolar/dipolar field. **CR 1935. 28 April 1998.**
Field mixed quadrupolar/dipolar, mainly quadrupolar
Poles of quadrupole beginning to appear
Current sheet is like the line separating halves of tennis ball
Polar coronal holes starting to elongate towards quadrupole poles
Mid-latitude coronal holes begining to form around magnetic poles

3. Mixed dipolar/quadrupolar field. **CR 1945. 25 January 1999.**
Field mixed quadrupole/dipole, mainly dipolar
Poles of quadrupole now appear
Current sheet tilted and warped
Polar coronal holes elongating and shearing off
Mid-latitude coronal holes clustering around quadrupole poles

4. Quadrupolar field. **CR 1955. 25 October 1999.**
Field now dominated by quadrupole
Poles of quadrupole clearly visible at mid-latitudes
Current sheet threads its way around poles.
Polar coronal holes now shrinking
Mid-latitude coronal holes cluster around quadrupole poles

5. Tilted dipolar field. **CR 1965. 24 July 2000.**
Field now mainly dipolar again
Poles of dipole are at mid-latitudes
Current sheet highly inclined but moderately flat
Polar coronal holes now disappeared
Mid-latitude coronal holes cluster around dipole poles

6. Tilted dipolar field. **CR 1975. 23 April 2001.**
Field mainly dipolar
Poles of dipole are at mid latitudes
Current sheet tilted, but still relatively flat
Polar coronal hole of negative polarity appeared at N pole
Mid-latitude coronal holes clustered around dipole poles

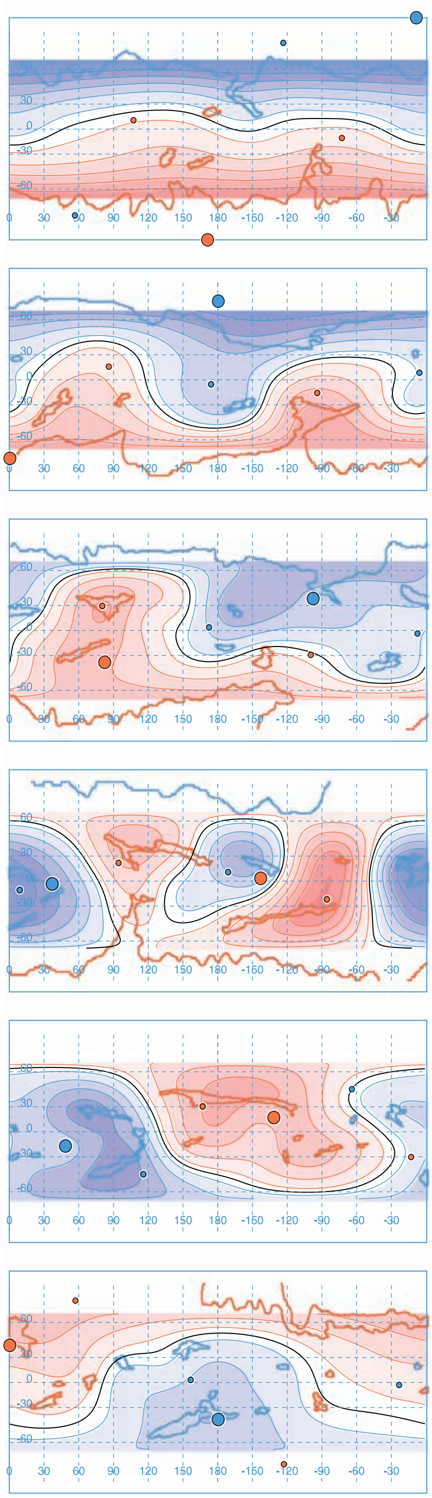

Figure 3a. Six examples of WSO source surface field maps for Carrington Rotations 1925, 1935, 1945, 1955, 1965, and 1975, which cover the period July 1997 to April 2001, plotted with a Mercator projection. Each plot shows the contours of the Sun's source surface magnetic field at 2.5 Rs with superimposed on it the location of the boundaries of the coronal holes. Positive fields are blue, and negative fields red. The steps in the shading range from -30 to $+30$ μT. The shading shows the regions of high field strength and thereby the positions of the maxima and minima of the field, which correspond to the positions of the poles of the magnetic field at the source surface. The positions of the outlines of the coronal holes are plotted on top of the magnetic field contours, again with blue signifying positive, and red signifying negative polarity. Superimposed on top, in black, is the position of the neutral line, or current sheet.

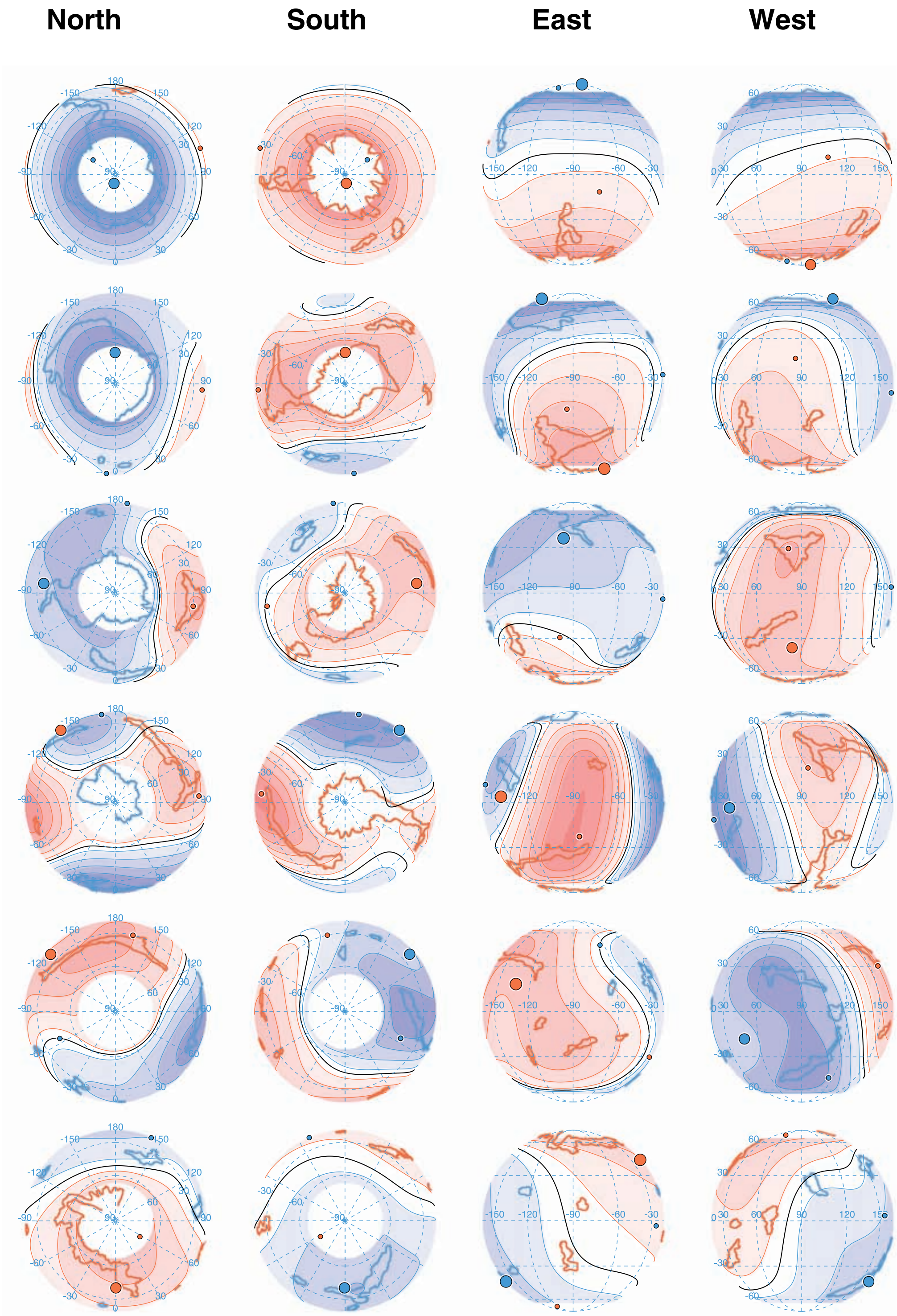

Figure 3b. Six examples of WSO source surface field maps for Carrington Rotations 1925, 1935, 1945, 1955, 1965, and 1975, which cover the period from July 1997 to April 2001. For each rotation, four plots are shown plotted with an orthographic projection, showing the view from a north, south, east and west heliographic position. Each plot shows the contours of the Sun's source surface magnetic field at 2.5 Rs with superimposed on it the location of the boundaries of the coronal holes. Positive fields are blue, and negative fields are red. The steps in the shading range from −30 to +30 μT. The shading shows the regions of high field strength and thereby the positions of the maxima and minima of the field, which correspond to the positions of the poles of the magnetic field at the source surface. The positions of the outlines of the coronal holes are plotted on top of the magnetic field contours, again with blue signifying positive, and red signifying negative polarity. Superimposed on top, in black, is the position of the neutral line, or current sheet.

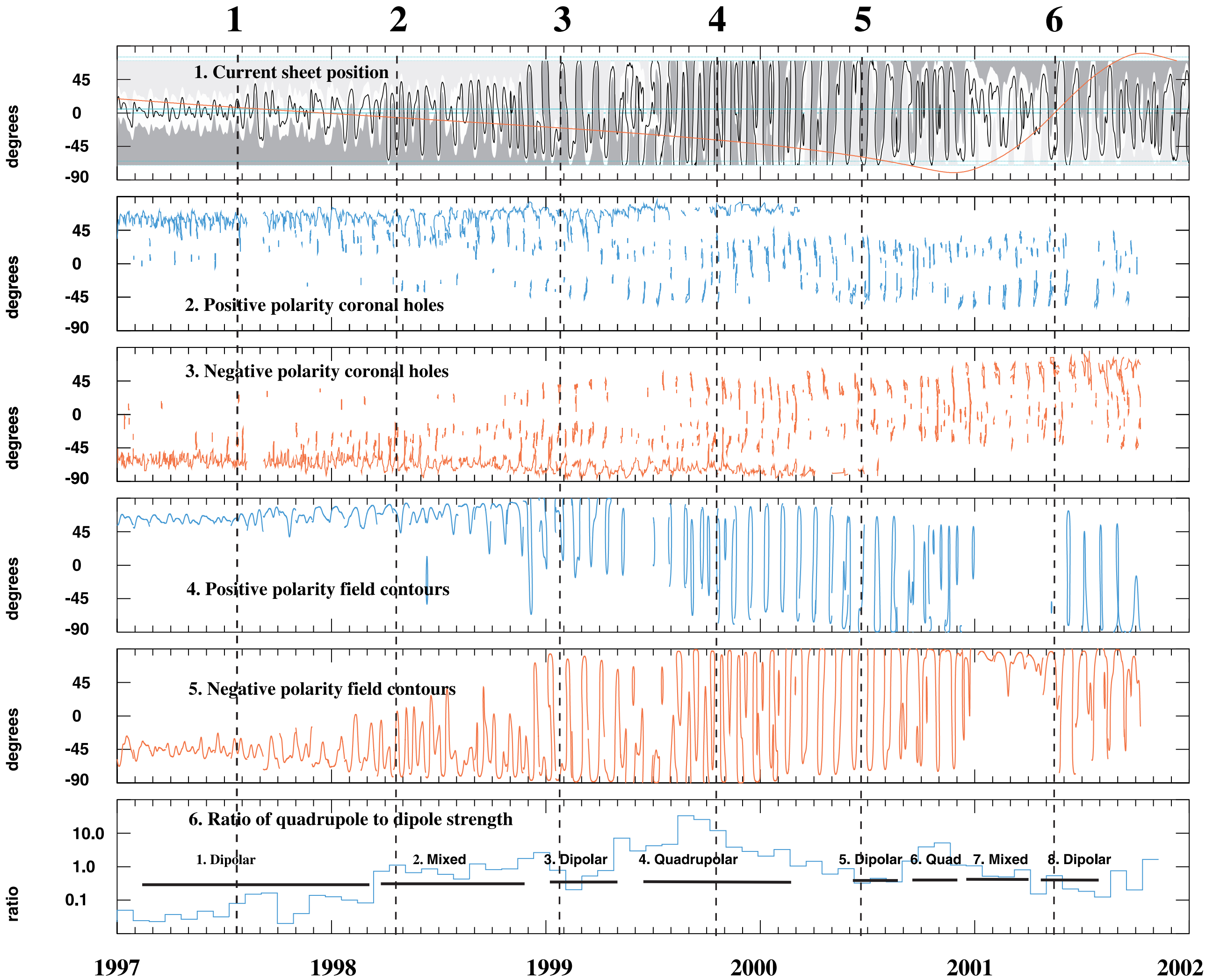

Figure 4. Panel 1 shows the locus of the current sheet on the Sun, and, in red, the trajectory of the Ulysses spacecraft. Panels 2 and 3 show the positions of the positive (blue) and negative (red) coronal holes. Panels 4 and 5 show contours of equal positive (blue) and equal negative (red) magnetic field strength on the source surface. Panel 6 shows the ratio of the strength of the quadrupole to the dipole. Vertical dashed lines show the times of the examples shown in Figures 3a and 3b.

magnetic poles were co-located with the heliographic poles, with the positive magnetic pole at the north heliographic pole, and the negative one at the south pole. In 1998, the two magnetic poles began slowly to drift equatorward across the disc of the Sun, crossing the center of the disc in 1999, each dipole pole at times splitting up into two quadrupole poles, such as in mid- and late 1998, late 1999, and early 2000. At the end of 2001, the positive magnetic pole was almost at the southern heliographic pole, and the negative pole almost at the North Pole.

[42] Panels 2 and 3 show how the coronal holes change. In 1997, one large positive hole was observed at the North Pole (Panel 2), and one large negative hole (Panel 3) at the South Pole. In 1998, these holes began to contract, and small midlatitude holes started appearing. The site of these holes slowly moved across the disc at the same rate as the magnetic poles, splitting up into what appears to be two tracks as they crossed over the disc. By the end of 2001, a negative polar coronal hole had reappeared at the north heliographic pole, while the positive southern hole had not yet reappeared.

[43] Panel 1 shows how during this period the computed current sheet changed from being a relatively flat current sheet in 1997 to a highly inclined current sheet in 1999, 2000, and 2001. The periodicity of the current sheet trace shows if the magnetic field is dipolar or quadrupolar. A dipolar field has a periodicity of around 27 days, such was observed in early 1999, whereas a quadrupolar field has a periodicity of around 13.5 days (such as during late 1999).

[44] One of the most striking features is the relative stability of the field during each period, followed by a rapid transition from the one relatively stable period to the other. These abrupt changes in the Sun's field, as they propagate outwards from the Sun, can influence the propagation of energetic and cosmic ray particles and were most likely responsible for some of the cosmic ray modulation effects seen at these times [*Sanderson et al.*, 2001]. The transition from Period 1 to Period 2, from dipolar to mixed, can

clearly be seen in the first panel, where the current sheet locus changes suddenly from one cycle to two per rotation near the equator, remaining so for the whole of Period 2. At the end of Period 2, the locus of the current sheet position changes from two cycles per rotation to one cycle as the field becomes dipolar again. This would correspond to a change from the fourth to second sectors at the Earth's location. This can clearly be seen in Panel 1, although a small warp in the current sheet at southern latitudes made the current sheet at Ulysses latitudes look quadrupolar.

[45] The field changed from dipolar to quadrupolar at the end of Period 3, coincident, in mid-1999, with a major disruption of the current sheet. The field then remained quadrupolar (two cycles per rotation in Panel 1, and therefore four sectors at Earth) for nearly 1 year. The coronal field then changed four times, back to a dipolar, quadrupolar, mixed, and then dipolar field.

[46] There is a clear relation between the position of the coronal holes and the position of the dipole axis. As the dipole axis started to move away from being aligned along the spin axis, the size of the polar coronal holes diminished, reaching almost zero when the axis was perpendicular to the spin axis (late 2000). The site of the coronal holes slowly drifted across the surface of the Sun in concert with the motion of the dipole as it moved across the Sun's disc. The impression this gives is that parts of the coronal hole elongated toward lower latitudes, and broke off into groups of smaller like-polarity holes as the poles approached the midlatitude regions. At the same time as the field became quadrupolar, multiple groups of like-polarity midlatitude coronal holes appeared, grouped around the magnetic poles.

[47] The distribution of coronal holes will determine where in the heliosphere high-speed flow will be observed. In the configuration of Panel 1 of Figure 3, high-speed flow will only be observed in polar regions, similar to the observations earlier of *Phillips et al.* [1994]. With the configuration of Panels 2–6 of Figure 3, high-speed flow will also be observed at low latitudes, but since it comes from the midlatitude coronal holes, the flow will be sporadic. With the configuration of Panel 5 of Figure 3, the polar coronal holes were almost nonexistent, which meant only low-speed flow was observed over the poles [*McComas et al.*, 2001].

[48] The highly tilted current sheet is ideal for the formation of interaction regions in the solar wind. The location of regions where particles are accelerated, the interaction region, is determined by the location of the boundary between the high speed and low speed flow. With the configuration of Panel 1 of Figure 3, interaction regions were virtually nonexistent. With the configuration of Panels 2–6, interaction regions such as stream interaction regions (recently defined by *Gosling et al.* [2001]), and co-rotating interaction regions that did not persist more than a few rotations were seen all the way up to high latitudes.

[49] As mentioned earlier, we expect the modeled current sheet to propagate out ballistically at least to 1 AU, if not to 2 or 3 AU without too much distortion, such as shown by *Suess and Hildner* [1985], *Roelof et al.* [1997], *Neugebauer et al.* [1998, 2003], and *Sanderson et al.* [1999]. This will determine the number of magnetic sectors seen by the observer. A rather flat current sheet with close to zero inclination such as in Panel 1 of Figure 3 will give rise to a somewhat indeterminant configuration at 1 AU, but a single sector at high latitudes. The configuration of Panels 2 and 4 of Figure 3, due to a substantial quadrupole component, will give rise to four sectors at low latitudes at 1 AU and even at moderately high latitudes, while the configuration of Panels 3, 5, and 6 of Figure 3 will give rise to two sectors at 1 AU and at even the highest latitudes. With the inclination of the current sheet close to around 90°, as shown in Panels 5 and 6 of Figure 3, two sectors were seen almost all the way to the poles [*Sanderson et al.*, 2001; *Smith et al.*, 2001].

7. Summary and Conclusions

[50] We have shown here, using new observations and analyses of the terms of the expansion of the potential field source surface model, how the axis of the dipole rotated during the last 22-year solar cycle, and, in particular, how during the 5 years around the recent solar maximum, the dipole moved from being aligned antiparallel to the spin axis around solar minimum to being aligned perpendicular to the spin axis around solar maximum. Eventually at the next solar minimum, the dipole will be aligned parallel to the spin axis.

[51] We have also shown how the magnitude of the quadrupole increased as solar maximum was approached and that the quadrupole poles directions remained substantially in the equatorial plane.

[52] Using the contours of the field, we have shown how the poles of the field moved and developed during the same 5-year period, the poles slowly tracking across the disc, and at time developing into a quadrupole field, and discussed how this influenced the heliosphere. At this time, the Sun was effectively on its side as far as the magnetic field was concerned, the axis of the dipole being approximately perpendicular to the spin axis.

[53] At these times, the current sheet was tilted and warped, and threaded its way around the poles of the magnetic field, reaching up to high latitudes with a shape not unlike the line that separates the two halves of a tennis ball.

[54] In late 1999, close to solar maximum, which was just before the Ulysses fast latitude scan, the quadrupole term dominated, and the current sheet was substantially warped. Surprisingly, for a short time just after solar maximum when the dipole axis was nearly perpendicular to the spin axis, the strength of the quadrupole component was small in comparison with the strength of the dipole. This coincided with the first part of the Ulysses southern polar pass (Period 5, Figure 4, early and mid-2000), and gave rise to a rather flat and highly tilted current sheet [*Sanderson et al.*, 2001; *Smith et al.*, 2001]. Later in 2000 (Period 6), as Ulysses passed over the southern pole, the field became mainly quadrupolar. During the in-ecliptic part of the Ulysses fast latitude scan (Period 7, early 2001), the field was mixed quadrupolar and dipolar. Finally, during the northern polar pass (Period 8, mid-2002) the field was mainly dipolar again.

[55] We have combined magnetic field data and coronal hole data over an extended period of time, and shown for the first time how polar coronal holes decayed in size as solar maximum was approached, parts of them elongating and extending to lower latitudes, and shearing off as the dipole tilted. The sites where the coronal holes were located followed the poles of the coronal field as they tracked across

the disc, at the same time splitting up into smaller multiple coronal holes.

[56] These configurations stayed stable for a few rotations, and were then followed by abrupt changes, which then propagated out into interplanetary space.

[57] **Acknowledgments.** This paper is dedicated to the memory of Karen Harvey. Karen passed away on 30 April 2002 after a long illness. Despite her long illness, Karen was still courageously able to make a substantial contribution to this paper. She was a great inspiration to us all. NSO/Kitt Peak data used here are produced cooperatively by NSF/NOAO, NASA/GSFC, and NOAA/SEL. KLH research was supported by NSF Grant ATM-9713576. The Wilcox Solar Observatory is supported by NSF, NASA, and the Office of Naval Research. The authors gratefully acknowledge useful discussions with Joe Giacalone, Randy Jokipii, Joseph Kota, Karel Schrijver, and Mike Schulz. We thank Arjan Hulsbosch for valuable help in the preparation of the diagrams. We acknowledge the use of the Ulysses Data System in the preparation of this paper.

[58] Arthur Richmond thanks Robert J. Forsyth and Yan Li for their assistance in evaluating this paper.

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