THE LARGE-SCALE STRUCTURE OF THE HELIOSPHERIC CURRENT SHEET DURING THE ULYSSES EPOCH

J. TODD HOEKSEMA
Center for Space Science and Astrophysics
Stanford, CA 94305-4055 USA
JTHoeksema@SOLAR.Stanford.EDU

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Abstract. Ulysses is traversing the Sun's polar regions for the first time a year or two before solar minimum. If the heliospheric magnetic field behaves as we expect, the heliospheric current sheet (HCS) during this stage of the sunspot cycle should be quite stable and lie nearly flat, close to the equator. The high latitude solar fields should be unipolar and nearing their maximum strength. The overlying polar coronal holes should be well developed, producing a nearly uniform high-speed solar wind. Because the Sun's polar fields live longer than any other solar magnetic phenomenon, Ulysses will remain within a single coronal hole for an extended period and probe its structures in a unique way.

Of course everything will almost certainly not turn out to be as quiet and well-ordered as we expect. We know now that the photospheric field strength in the northern polar cap is less than the south. What will this mean for the solar wind speed and the magnitude of the interplanetary magnetic field? Solar and coronal observations suggest that the first magnetic signatures of the next solar cycle may already be emerging at high latitudes. Will Ulysses sense these fields "leaking" into the heliosphere or is the interplanetary magnetic structure completely dominated by the large-scale field as the models currently predict? How will the sources of variations in field, velocity, density, and composition fit into our conceptual picture?

Ulysses' rapid dash from south to north provides a unique opportunity to determine the latitudinal width of the equatorial region influenced by the HCS. This rapid change in latitude over a short interval during which the structure should be stable, should provide a definitive measurement of the latitudinal gradients of various quantities relative to the heliomagnetic equator.

In the next several years Ulysses will gradually decrease in latitude, eventually meeting the HCS as it gradually expands away from the equator during the rising part of the cycle. It will then race the HCS to the poles as maximum approaches. The situation in six years, at solar maximum, will be radically different. There will be no unipolar high latitude field, the HCS will extend to the poles, existing structures will be less stable, and there will likely even be multiple current sheets. Ulysses will have another opportunity to confirm or disprove our understanding of the high latitude heliosphere in a much different environment. The extended mission is essential to advance our understanding of the heliospheric field at the extremes of the solar cycle.

Key words: Heliospheric Current Sheet – Ulysses

1. Modeling the Heliospheric Current Sheet

Attempts to model coronal and interplanetary magnetic fields from photospheric observations have been made since the late 1960's (Schatten et al., 1969; Altschuler and Newkirk, 1969). Such models make simplifying assumptions about the physics to compute the magnetic field configuration

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near the Sun. At some height, often called the source surface, one assumes that the magnetic field configuration becomes frozen into the accelerating coronal plasma. The neutral line, dividing regions of opposite radial field at the source surface, is swept radially outward by the solar wind to define the 3-dimensional surface called the heliospheric current sheet (HCS). Fig. 1 shows the computed location of the HCS for the last solar cycle.

While the field configuration predicted at the base of the solar wind compares favorably with coronal data (Wilcox and Hundhausen, 1983; Bruno et al., 1984; Sime and McCabe, 1990) and with in-ecliptic spacecraft measurements of the interplanetary magnetic field (IMF) polarity (Hoeksema et al, 1982, 1983), it is generally difficult to verify the HCS location at high latitudes. The disappearance of the IMF sector structure during Pioneer 11's sojourn at just 16° north in 1976 demonstrated that the Sun's polar field dominates the heliospheric field configuration at solar minimum (Smith et al., 1978). Pioneer and Voyager measurements at high latitudes (and large heliocentric distances) confirmed the flattening of the sector structure again at the following minimum (Gazis, et al, 1989). However, making a detailed comparison between observations and predictions in the inner heliosphere and the outer heliosphere is very difficult because of dynamic processes acting in the solar wind (Behannon et al., 1989). Until Ulysses, sporadic cometary observations have provided the only *in situ* confirmation that the HCS extends to high latitudes (Neidner and Brandt, 1978; see also Farnham and Meech, 1994, and references therein). Ulysses passed below the maximum latitude of the current sheet enroute to the south pole in April, 1993 at about 30° S (Smith, et al., 1993).

The potential field model postulates that the coronal fields are effectively current free between the photosphere and a larger concentric shell called the source surface. Observations constrain the field at the photosphere, while at the source surface the model enforces a purely radial field configuration. These conditions are enough to determine a solution that reproduces fairly well what we know about the coronal field. The height of the source surface is fixed by physical considerations and optimized to match observations. Until recently the model apportioned the measured line-of-sight photospheric field to both a radial and a meridional component. In this case the fields in the Sun's polar caps were relatively weak. Observations of the annual variation of the polar fields (Svalgaard et al., 1978) and the 16° Pioneer observations (Smith et al., 1978) indicated that the Sun's strong polar fields must be included in the model. Setting the source surface radius at 2.5 R_s and adding a very sharply peaked 10 G polar field enabled the calculations of the ecliptic polarity to match the daily measurements about 80% of the time over the solar cycle (Hoeksema et al., 1982, 1983).

More recently Wang and Sheeley (1992) proposed treating the surface fields as purely radial, a very reasonable assumption at that height in the

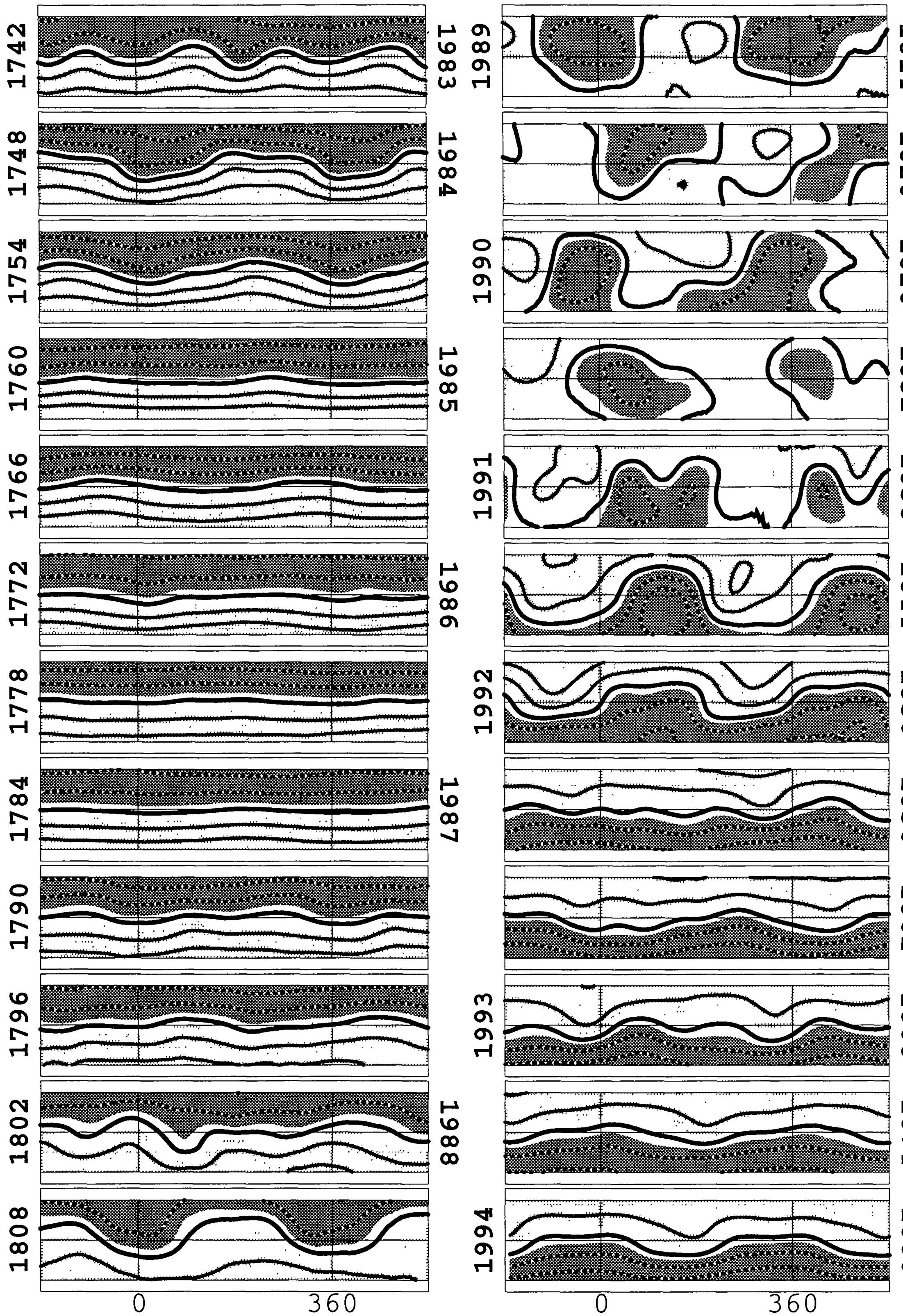


Fig. 1. Each panel shows the source surface field in a window two rotations wide centered on the indicated Carrington rotation. The neutral line is bold and negative regions are more darkly shaded. This shows every 6th rotation for the last 11 years (the first rotation within each year is indicated in the inner margin).

photosphere. This effectively increases the polar field strength and obviates the need for the indirect polar field correction. Except as noted, results in this paper use this radial inner boundary condition and a source surface radius of 3.25 R_s. With these conditions the daily predicted IMF polarity matches the *in situ* data with a correlation coefficient of about 0.59 in the interval from 1976 to 1988. The correlation ranges from 0.52 at solar minimum in 1976-8 to 0.71 in the declining phase, 1982-4. The overall in-ecliptic agreement depends relatively little on the source surface radius except at solar minimum. The HCS computed with the radial surface field is generally flatter and agrees better with the timing of Ulysses' last sector observations (Phillips et al., 1994). Potential field models do not correctly determine the IMF strength, but one such effort is discussed below.

2. The Source of the Heliospheric Field

The field lines at the source surface are open, by definition. Following open field lines to the photosphere shows that essentially all the IMF comes from coronal holes (Levine, 1982, Wang & Sheeley, 1992). Fig. 2 shows how the photospheric field connects to the open flux in the corona in March 1993, just before Ulysses passed south of the HCS. The footpoints in Panel 3 are traced from an evenly spaced grid on the source surface. In the declining and minimum phases nearly all of the heliospheric field originates in the polar coronal holes; the rest comes from low-latitude extensions of the polar hole.

The divergence of the field is inversely related to the solar wind speed (Levine, 1978; Wang & Sheeley, 1990, 1991; Sheeley et al, 1994). Low divergence in the lower panel of Fig. 2 indicates expected regions of high solar wind speed, e.g. in the northern polar region and at mid northern latitudes near 330° and at low southern latitudes near 60°. The HCS forms over closed coronal features that constitute the streamer belt. The HCS always lies over areas of large field line divergence that generate slow solar wind.

While the large-scale structure of the coronal field is stable for long periods of time, there are occasions when the field rapidly rearranges itself. Fig. 3 shows a dramatic example of such an episode in May - July, 1992, when over just a couple rotations the long-standing coronal pattern consisting of an extension of the southern polar hole around 60° was replaced by a totally new structure with the polarity of the northern hole. The north-south arcade at 90° was replaced by an east-west arcade in the south (left column). The rearrangement of the open field regions is shown better on the right. Panels for CR 1850, 1856, and 1862 in Fig. 1 help to put this in context. This reorganization was reflected in a major shift in the IMF sector structure pattern observed by Ulysses (Balogh et al., 1993).

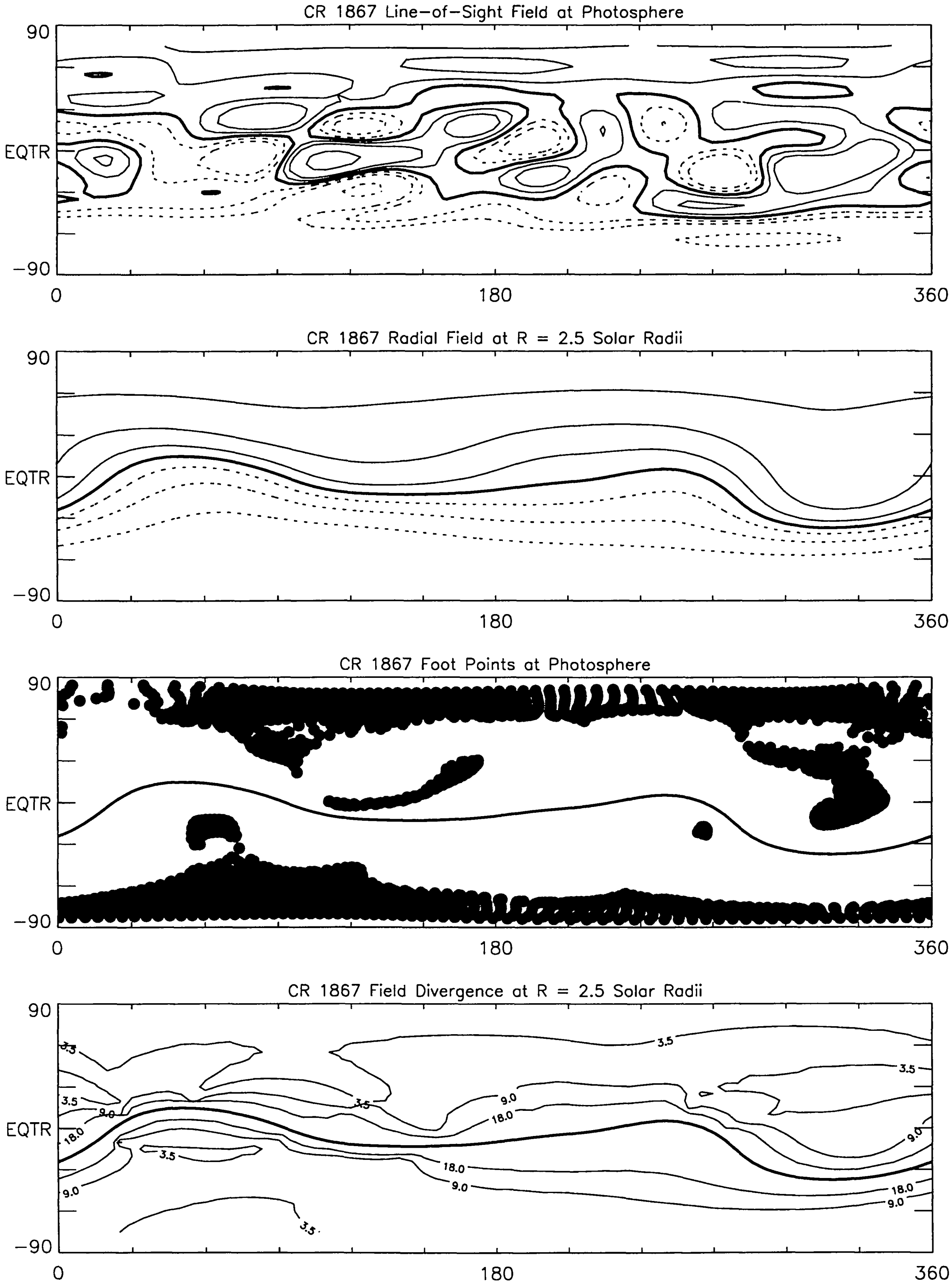


Fig. 2. Panel 1 (top) shows a Carrington map of the photospheric magnetic field in March 1993. Contours are at 0, 1, 2, 5 and 10 G. Dashed contours show negative field. The second panel shows the field calculated with the source surface at 2.5 R_s. Contours are at 1% of the photospheric level. Dots in the third panel show the foot points of open fields mapped back to the photosphere. The divergence of flux tubes is related to the solar wind velocity (bottom panel). Bold lines in panels 3 and 4 are the source surface neutral line.

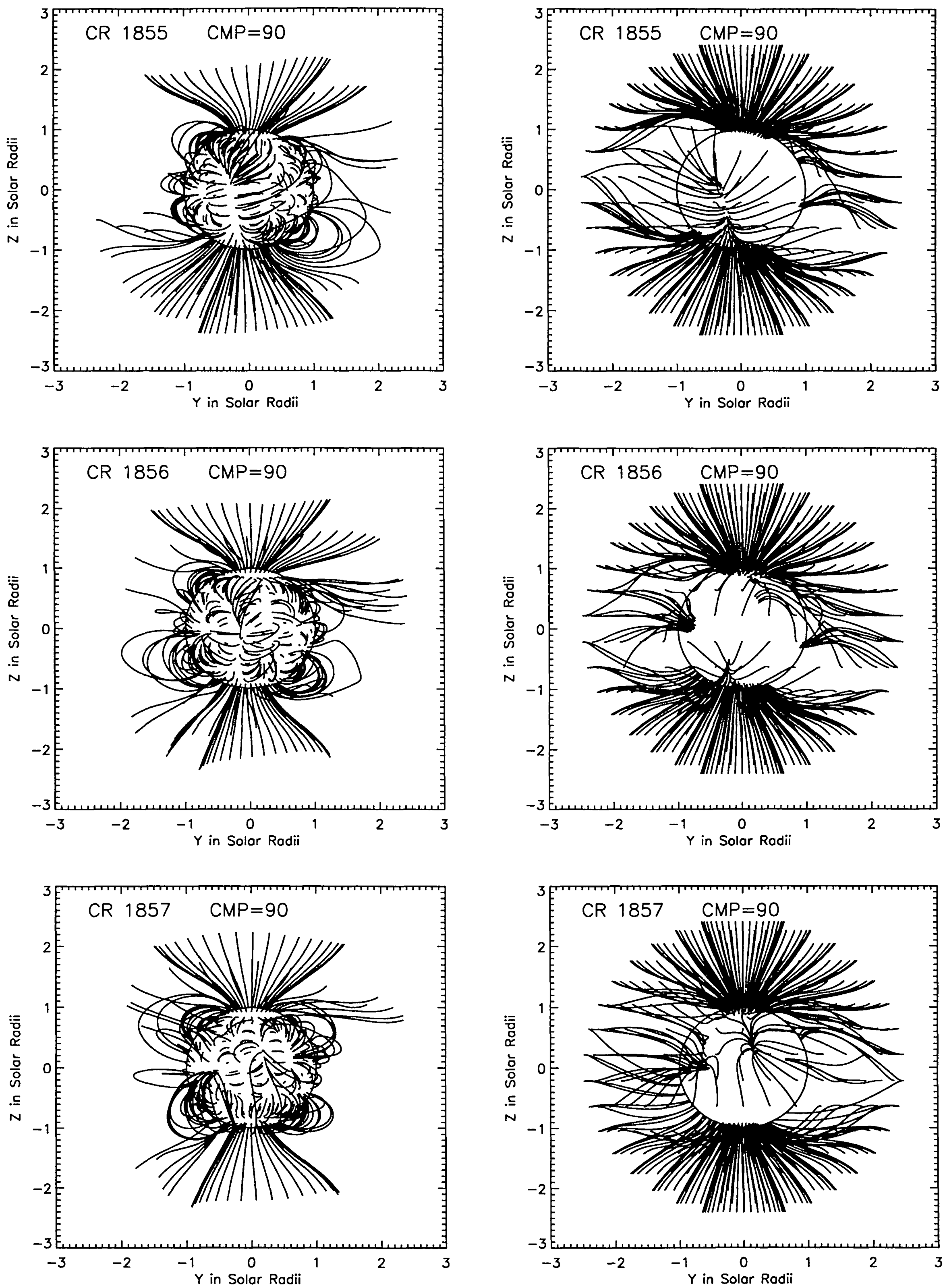


Fig. 3. The coronal field changed its configuration in the spring of 1992. The left panels show the field lines originating on a regular grid in the photosphere for CR 1855, 1856, & 1857. Only open field lines traced downward from 2.5 R_s are shown on the right. Notice the decay of the vertical arcade near CMP 90° and the development of a horizontal structure in the south. The northward extension of the negative southern coronal hole in CR 1855 is replaced by low latitude open positive field regions.

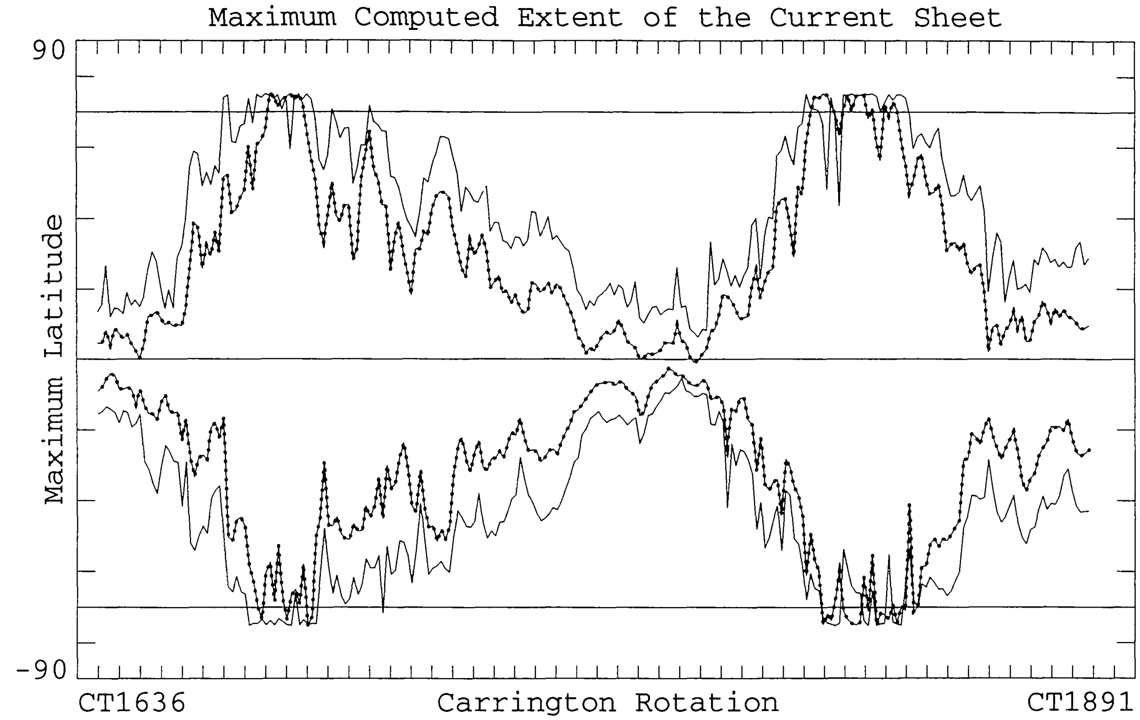
3. The High-Latitude HCS in the Ulysses Epoch

Stability characterizes the coronal and heliospheric field during the declining and minimum phases of the solar cycle, particularly at high latitudes. The strong polar fields confine the HCS to the equatorial region for several years around solar minimum. Near minimum the ecliptic and the HCS are never far apart, explaining the corresponding minimum in average solar wind velocity near Earth. In the declining phase of Cycle 22, even more than in Cycle 21, the (sometimes tilted) dipole field dominates the higher order contributions to the HCS shape everywhere except near the "heliomagnetic equator." Fig. 4 (top) shows that the computed HCS currently reaches to about 25° in the south and about 10° in the north. The predicted latitudes are up to 20° higher when using the standard potential field model (light, solid curve). The maximum latitude and complexity of the HCS structure vary through the solar cycle (see also Fig. 1 and from one cycle to the next.

Ulysses will be immersed in the polar coronal holes for several months. The photospheric sources of the polar holes should change little, so the solar wind should be uniform at high latitudes. Inhomogeneities should arise from variations inherent to the acceleration processes rather than the evolution of the photospheric fields. Ulysses' unique perspective at solar minimum allows this kind of coronal hole monitoring for the first time.

The photospheric field does not remain completely static. In fact the first precursors of Cycle 23 may be erupting at high latitudes now. For example, Harvey (1992) shows that ephemeral regions of the new cycle emerge at high latitudes several years before sunspot minimum, as do Ca^+ plage regions. Evidence for an extended high-latitude solar cycle is also seen in coronal brightness observations (Altrock, 1988). Effects of such photospheric field irregularities may find a way to "leak" out into the high latitude heliosphere.

The polar fields are not strictly antisymmetric, each hemisphere evolves semi-independently. The lower panel of Fig. 4 shows that field strength in the region from about 55° to the pole is currently as much as 60% larger in the south than the north. This was true near the minimum in 1986 as well. The polar fields were roughly equal in 1976. Note that the large annual variation of the line-of-sight polar fields is caused by the strongly peaked distribution of the polar field and the inclination of the ecliptic to the solar equator. This imbalance of north and south results in differences between the hemispheres. One would expect differences in high-latitude IMF strength and solar wind velocity. The HCS reaches to higher northern latitudes as well. The differences between Ulysses' two polar passes should tell us some interesting things about the dependence of coronal holes and solar wind acceleration on absolute field strength. Another difference to look for will be the rotation rate of the magnetic field pattern; Hoeksema and Scherrer (1987) showed that the computed coronal field pattern rotated about 4%



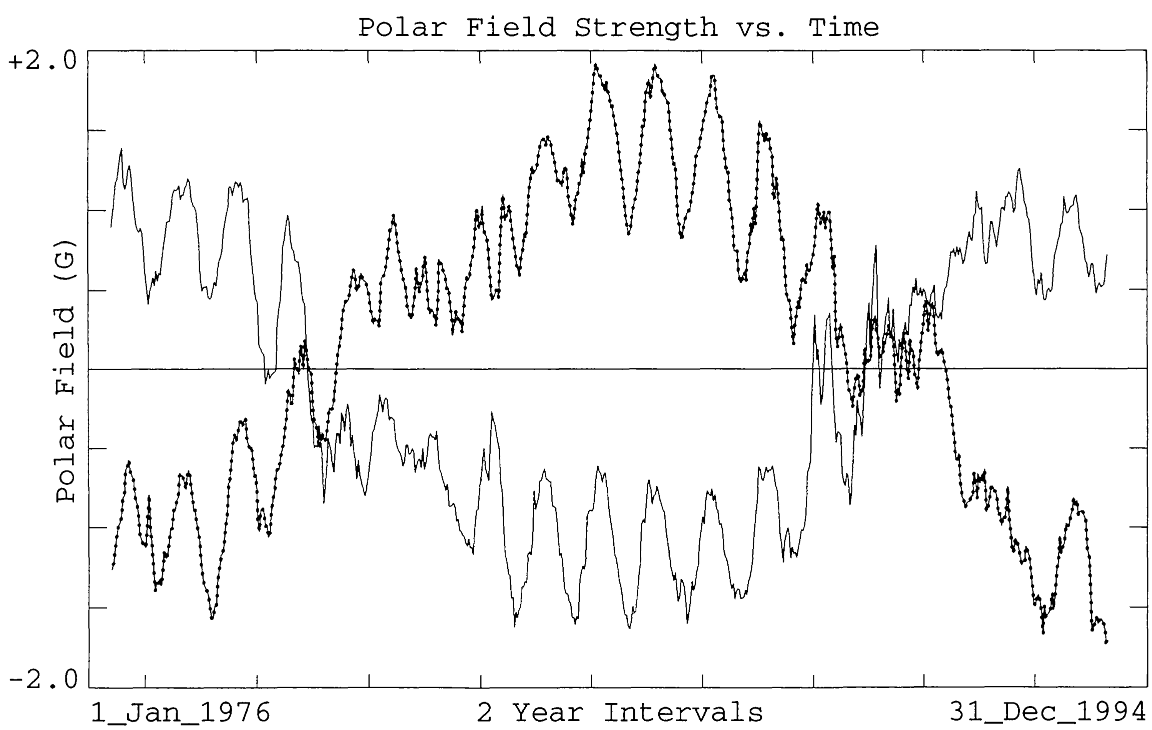


Fig. 4. The upper panel shows the maximum latitude reached in each hemisphere by the computed heliospheric current sheet from 1976 to 1994. The solid line represents the standard potential field model with $R_s s$=2.5 R_s; the dotted line shows the better radial model result with $R_s s$=3.25 R_s. The measured line-of-sight polar region field strength has a large annual variation due to the 7.25° inclination of the ecliptic to the solar rotation axis. The south polar field was much stronger than the north during two most recent solar minima. They were roughly equal in 1976.

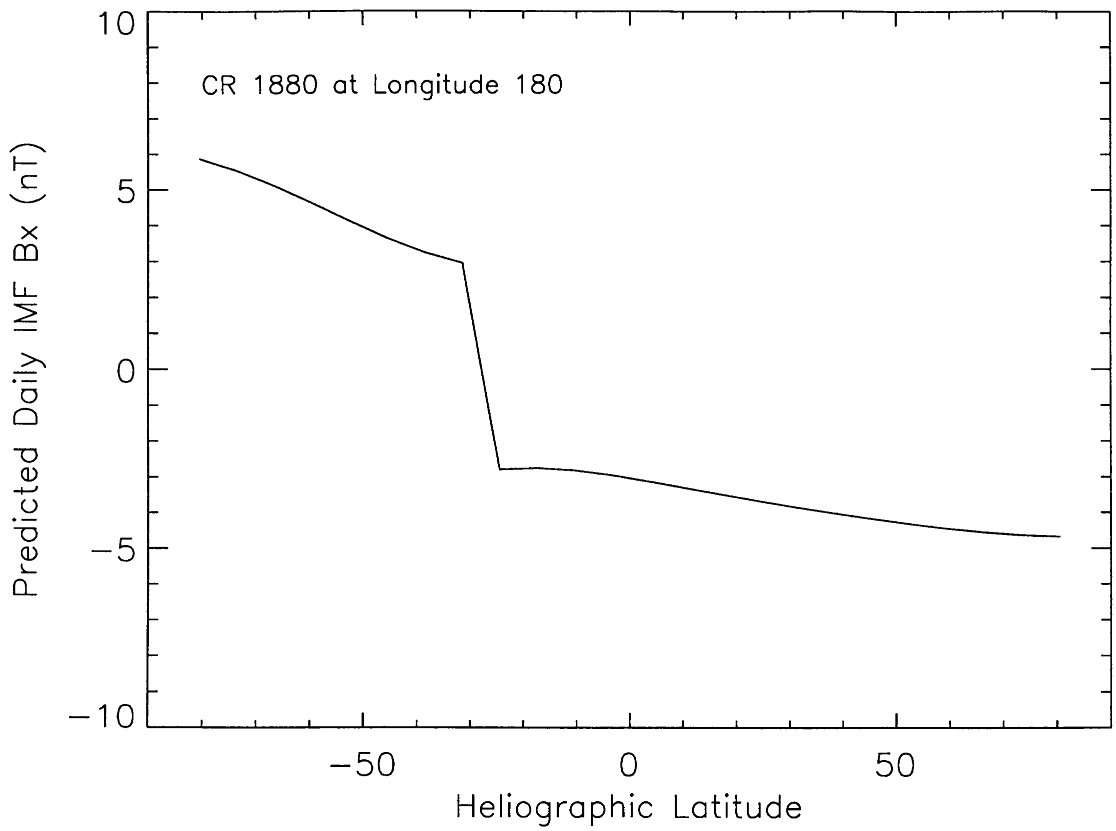


Fig. 5. The composite coronal field model predicts the sunward component of the IMF versus latitude for longitude 180 of Carrington Rotation 1880. The south is stronger than the north and more sharply peaked. Note that Bx is -Br. (From Zhao and Hoeksema, 1994a)

slower in the south during Cycle 21.

Recently Zhao & Hoeksema (1994b) have developed a composite model that combines many of the best features of the potential field model, Bogdan and Low's magnetostatic model that includes horizontal currents (1986) and Schatten's current sheet model (1971). Besides being more physically realistic, the model makes reasonable predictions of the in-ecliptic radial IMF magnitude and direction. Ulysses will provide the high-latitude test of the prediction shown in Fig. 5. At the computed Carrington longitude the HCS lies between 25° and 30° S and the field strength is sharply peaked, particularly in the south.

4. The Transit Phase and the Extended Mission

Between the southern and northern polar passes Ulysses will move rapidly through the equatorial region. Traditionally the solar magnetic field is extremely stable during this part of the cycle, thus the spacecraft should get a fairly clear reading of how various heliospheric phenomena vary with lata fairly clear reading of how various heliospheric phenomena vary with latitude, independent of temporal evolution. Depending on the longitudinal phase of the HCS structure with respect to the trajectory, it should be possible to detect differences in latitudinal extent of the HCS in the two hemispheres, though the neutral line will be fairly flat. It will also be interesting to learn about the size of the belt where the velocity is affected by the HCS, not to mention the gradients in cosmic ray intensity. Previous probes have been limited to relatively low latitudes and have been forced to compare measurements made at greatly different heliocentric distances and/or times.

The extended mission will encounter in very different circumstances. After the northern flyby in 1995 Ulysses will slowly head toward lower latitudes, eventually meeting the HCS again near the equator just after solar minimum. Then the race toward the poles will begin again, this time as the Sun approaches its maximum in 2000-2001. Both Ulysses and the HCS will move quickly poleward, neck and neck at first, but the HCS will probably arrive at the poles first. While Fig. 4 shows that extrapolations from one cycle to the next may be unreliable in detail (see also Suess et al., 1993), Fig. 1 clearly indicates that the heliospheric current sheet will extend to high latitudes. There may, in fact, be multiple current sheets in the heliosphere near solar maximum.

Even if we develop confidence in our understanding of the relatively simple inner heliospheric field at minimum from the presently available data, exploring the high latitude heliosphere at solar maximum will lead to important discoveries because conditions are expected to be completely different. The polar fields will likely have mixed polarities and will almost certainly be weak. In a certain sense this will make the high latitude heliosphere more like the ecliptic at maximum, but the region will be much less influenced by active regions.

5. Conclusions

The heliospheric current sheet will remain fairly flat for the next several years, with only small warps apparent at low latitudes to distort it from a simple slightly tilted dipole configuration. The maximum latitudinal extent of the structure will continue to decrease through solar minimum and only begin to rise a couple of years later. The coronal and heliospheric structure will continue to remain stable, though episodes of large-scale field rearrangement can occur in the corona.

Tradition suggests that the solar wind in the polar regions will be fairly homogeneous, as far as the magnetic field is concerned. Ulysses will cross the HCS only when it travels near the solar equator from now until the late 1990's. If there are nonuniformities in the solar wind that are not due to dynamic effects caused by lower latitude activity, they may be the result of high-latitude precursors of Solar Cycle 23.

There are significant differences between the northern and southern polar fields. The southern cap is currently stronger; therefore solar wind conditions over the north pole should be different. Because the stable polar fields are sharply peaked near minimum, models predict that the radial component of the IMF will increase with latitude; more in the south than in the north. Such will likely not be the case at solar maximum. Rotation rates of the magnetic source pattern may also differ between north and south, as it has in past cycles.

The solar wind velocity will remain high over the stable polar coronal holes, though the highest solar wind velocity is predicted for mid-latitudes over coronal holes that extend toward the equator. The rapid south-north transit in 1995 will be ideal for determining latitudinal variations in solar wind velocity and magnetic field strength.

The extended mission offers exciting possibilities for learning about the high-latitude heliosphere under radically different conditions. Experience gained from the current solar minimum will help place the more complex structures expected to be observed at solar maximum into some kind of reasonable perspective.

Contributions from other spacecraft, such as SOHO, will be very important for constructing a complete and consistent picture of the heliosphere throughout the solar cycle.

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