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Ulysses Observations of the Northward Extension of the Heliospheric Current Sheet

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Abstract. After passing through the northern polar regions of the heliosphere during the summer of 1995, the Ulysses spacecraft has been gradually returning towards lower equatorial latitudes, reaching 30°N in August 1996 at about which time low speed solar wind from the streamer belt was once again observed. This paper reports on the Ulysses magnetic field observations, beginning from this time, concentrating on encounters with the heliospheric current sheet. These encounters restarted at a latitude of 25.5°N, a higher latitude than might be expected at solar activity minimum. We show that this early reappearance was due to a northward deflection of the current sheet caused by a long-lived active region at the corresponding heliographic longitude in the photosphere.

Introduction

Since early spacecraft observations of the heliospheric magnetic field it has been recognised that at low heliographic latitudes the magnetic field is split between sectors consisting of vectors pointing either towards or away from the Sun [e.g. *Wilcox and Ness*, 1965]. One of the interpretations of this phenomenon, involved the dominant dipole and weaker higher order components of the Sun's magnetic field being carried out into the heliosphere by the solar wind, the two polarities of the dipole being separated by a warped heliospheric current sheet (HCS) [*Schulz*, 1973]. Confirmation of this simple view of the HCS structure came when Pioneer 11 passed into a region of unipolar magnetic fields at a heliographic latitude of 16°N during 1975-76 [*Smith et al.*, 1978]. Direct measurement of photospheric magnetic fields from the Earth combined with associated modelling of coronal magnetic fields suggest that the maximum distance of the HCS from the solar equator is a function of the solar cycle [*Svalgaard and Wilcox*, 1974] with the HCS being closest to equatorial at solar minimum. As solar activity increases the HCS extends more and more poleward towards solar maximum at which time the polarity of the heliospheric magnetic field reverses in response to that of the underlying solar dipole.

As part of its mission to characterise the three-dimensional properties of the heliosphere [see *Marsden et al.*, 1996, for full details of the mission and orbit], the Ulysses spacecraft passed through the northern polar regions of the heliosphere during mid-1995. Since then Ulysses has been gradually returning to lower latitudes towards its next equatorial crossing in December 1997 at 5.4 AU. This paper reports on the magnetic field observations made as Ulysses once again began to encounter the streamer belt in August 1996, as first reported in the solar wind plasma observations of *Gosling et al.* [1997], with an emphasis on the behaviour of the HCS at this time.

The original Pioneer 11 excursion north of the maximum latitude of the HCS took place at a time of solar activity minimum. Subsequent excursions of spacecraft, other than Ulysses, into regions of unipolar field have occurred for Pioneer 11, again at 16°N during 1985-86 at the next solar minimum [*Smith*, 1989] and for Voyager 1 in the latitude range of 27.8-30.8°N in 1986-88 during the rising phase of solar cycle 22 and again beginning in 1994 at 32.5°N during the declining phase of the same cycle [*Burlaga and Ness*, 1993; 1996]. All the Ulysses passages across the maximum latitude of the HCS so far, have also taken place during the declining phase of solar cycle 22. The first occurred in 1993 at a latitude of approximately 30°S [*Smith et al.*, 1993; *Balogh et al.*, 1993] as Ulysses was travelling towards the south polar regions of the heliosphere. During the fast latitude scan of Ulysses from the southern to the northern polar regions in 1995, the extreme latitude crossings of the HCS took place at 10°S and 18°N [*Smith et al.*, 1995; *Forsyth et al.*, 1996], consistent with a pseudo HCS inclination of about 15°.

During 1996 solar activity as measured by monthly mean sunspot number was low and should be close to minimum. It was certainly lower than in March 1995 (at the time of the Ulysses fast latitude scan) and in the most recent sunspot number data [*Solar Geophysical Data*, April 1997, Pt. 1] there is no evidence of any rise in mid 1996 or more recently. Thus in principle there would be no reason to expect that the HCS tilt during 1996 would be any greater than that observed by Ulysses in 1995.

Observations

The observations presented in this paper were obtained by the magnetometer experiment on Ulysses [*Balogh et al.*, 1992] focusing on the time period depicted in Figure 1 from day 150 (29 May) of 1996 through to day 84 (25 March) of 1997. During this time Ulysses moved through a latitude range from 35.7°N down to 14.0°N, as shown along the top axis of the figure, and through a radial distance from 3.9 out to 4.9 AU from the Sun. The figure shows six hour averages of the magnitude and azimuth angle of the magnetic field measured at Ulysses. Also indicated are the Carrington Rotation numbers of the solar rotation periods corresponding to the intervals of data separated by the dotted vertical lines. These Carrington Rotation numbers have been assigned by mapping back the position of Ulysses to the sun using the solar wind velocity measured at Ulysses, assuming constant velocity with distance from the Sun, to determine the Carrington longitude at the solar wind 'source surface' from which a heliospheric magnetic field line observed at Ulysses is assumed to have originated. This calculation also assumes that the field line remains at a constant heliographic latitude. The Carrington Rotations indicated on Figure 1 are those with which the Ulysses data

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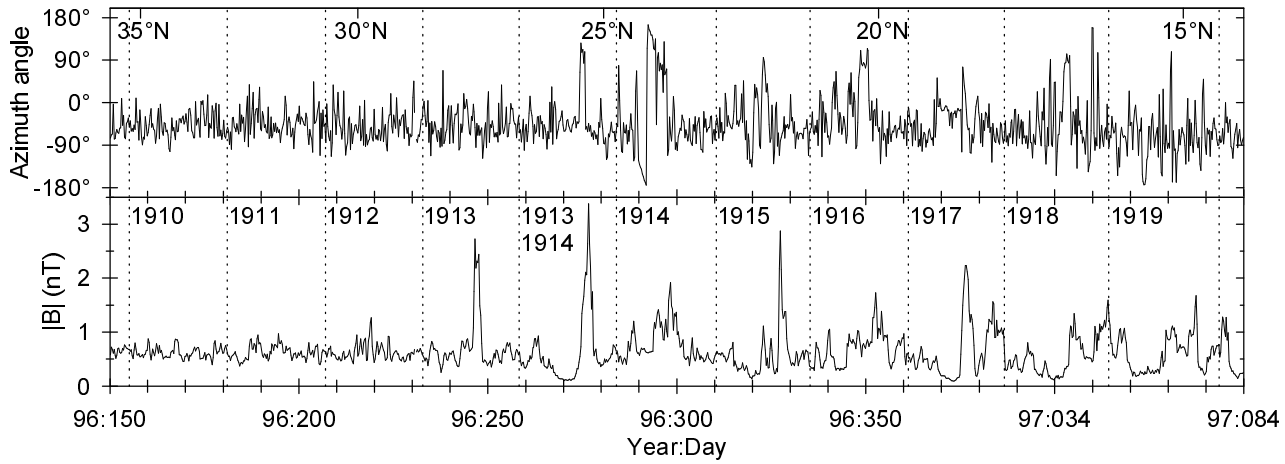

Figure 1. The azimuth angle (top) and magnitude (lower panel) of the magnetic field (6 hour averaged) measured at Ulysses between day 150, 1996 and day 84, 1997. The heliographic latitude of Ulysses is shown along the top axis. The vertical dotted lines give the approximate boundaries of the Carrington Rotations to which that part of the Ulysses data can be compared.

should be compared to solar observations made from the Earth. Note that due to the relative orbits of the Earth and Ulysses around the Sun, Ulysses was close to being on the directly opposite side of the Sun from the Earth for the interval labelled both 1913 and 1914 on the figure where there is maximum ambiguity in deciding with which interval of observations made from the Earth the Ulysses data should be compared; this being to a lesser extent true for the intervals either side.

Considering the early part of Figure 1 down to latitudes of 30°N, the behaviour of the magnetic field is typical of that observed in the unipolar fields and approximately constant high speed solar wind originating from the northern polar coronal hole. The field magnitude exhibits no evidence of any large scale compression and the azimuth angle corresponds, to a first approximation, to that of the Parker spiral direction. As described by *Gosling et al.* [1997] the first clear encounter of Ulysses with lower speed solar wind associated with the streamer belt occurred at a latitude of approximately 30°N. The corresponding return to high speed wind resulted in a weak compression in the magnetic field on day 219 (6 Aug.) and a weak reverse shock wave. One solar rotation later, in the interval labelled 1913 in Figure 1, as the latitude of Ulysses continued to slowly decrease, low speed solar wind from around the same longitude on the Sun produced a clear CIR (Corotating Interaction Region) signature in the magnetic field strength, again with only a reverse shock on day 248 (4 Sep.). Inspection of the azimuth angle in Figure 1 shows that for both of these first two cases Ulysses remained continually on outward directed magnetic field lines, north of the HCS.

In the subsequent interval, labelled both 1913 and 1914, the CIR was now bounded by both forward and reverse shocks and the azimuth angle plot shows the characteristic 180° switches associated with HCS crossings, indicating that Ulysses was sampling inward magnetic fields from south of the HCS for about 1.5 days beginning on day 274 (30 Sep.). This first encounter with the HCS by Ulysses as it returned from high northern latitudes took place at a latitude of about 25.5°N. The return HCS crossing back to northern magnetic fields was within the compression region of the CIR, indicating that the HCS had been 'swept up' as slow solar wind ahead of the CIR was accelerated. Mapping back the times of the two HCS crossings to the Sun using the measured solar wind speed indicates that Ulysses was observing southern hemisphere polarity magnetic fields approximately between Carrington longitudes of 249° and 231°.

While the above interval represents typical CIR and HCS behaviour, the following, labelled 1914 in Figure 1, was much more complex in that the recurrent CIR was preceded by a long duration coronal mass ejection (CME) event. This interval is shown in Figure 2 in greater detail where 17 days of magnetic field data (elevation and azimuth angles and field magnitude) are plotted through both the CME and CIR. The shaded section shows the duration of the CME deduced from its plasma signatures [*Gosling et al.*, 1997]. This event drove a forward shock wave which arrived at Ulysses late on day 287, then the CME itself arrived in the early part of day 288.

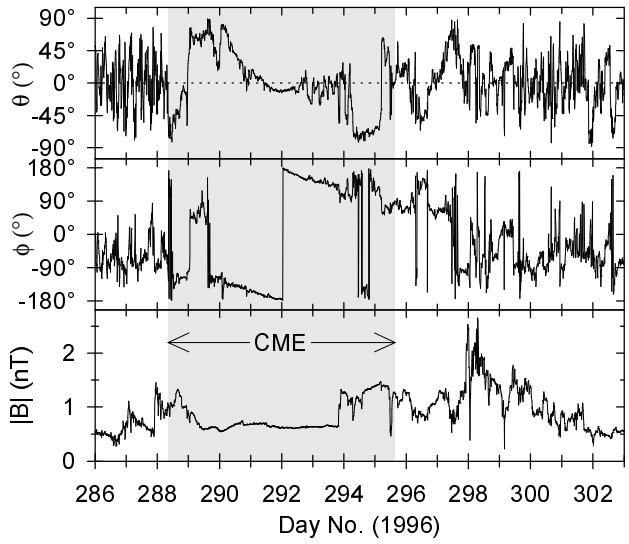

Figure 2. 10 minute averaged magnetic field elevation angle (upper panel), azimuth angle (centre) and magnitude (lower) covering days 286 to 302 (12 to 28 October) 1996 inclusive. The grey shaded area indicates the duration of the CME discussed in the text.

The CME had a clear magnetic cloud associated with it as can be seen on Figure 2 from the smooth rotations of the magnetic field angles within the shaded region. The 360° change at the start of day 292 is an artefact due to the azimuth angle rotating smoothly past 180°. Unusually, a forward shock wave was observed within the CME late on day 293, visible in the field magnitude on Figure 2. This CME is of particular interest from the point of view of this paper because of its interaction with the HCS. In the azimuth angle on Figure 2, we see that the field has the antisunward orientation of the northern hemisphere prior to the CME, but behind the CME (ending on day 295) the field has the sunward orientation of the southern hemisphere, and does so until a crossing of the HCS back to the northern hemisphere on day 297. Thus this event is similar to that discussed by *Crooker and Intriligator* [1996]. The field rotation between opposite sectors occurs as a broad rotation within the CME. The HCS is neither pushed aside nor draped around the CME; but is replaced locally by the CME.

For the intervals beginning with CR1915 it is difficult to pick out clear HCS crossings in Figure 1. In CR1915 there are field rotations which might be due to Ulysses being near the HCS but not fully crossing it. In 1916 the apparent region of opposite polarity field lies within a region exhibiting CME signatures in the plasma data. In 1917 there is an extended interval with close to 0° azimuth and elevation angles, indicating antisunward radial field lines. This is associated with a rarefaction region, indicated by the reduced magnetic field strength, and is followed by another CME with associated magnetic cloud. The next unambiguous pair of HCS crossings bound the 2 day interval of sunward magnetic field on days 36-37 (5-6 Feb.) of 1997 in CR1918, but again there appear to be no HCS crossings in the final interval shown (1919). The details of many of these specific cases are still under study.

To gain a first understanding of how the HCS behaviour at this time is related to the structure of the solar corona, we have compared the Ulysses HCS data with the neutral line on the Stanford University source surface maps, available via the Stanford web site or in *Solar Geophysical Data*. These maps are produced [e.g. *Hoeksema*, 1995] by extrapolating outwards the photospheric magnetic fields measured at the Wilcox Solar Observatory (WSO) using a potential field model with an outer boundary condition that the magnetic field lines are all open and radial by 2.5 solar radii from the Sun, the so-called 'source surface'. Magnetic fields originating from the northern and southern hemispheres are separated by the neutral line at the source surface, and thus the HCS observed at Ulysses should map back to the neutral line. One synoptic map is produced per Carrington Rotation as the Sun rotates as seen from Earth. For each of the Carrington Rotations in Figure 1 we determined the maximum heliographic latitude reached by the neutral line and the Carrington longitude at which this occurred. The results are shown in Figure 3. The maximum latitude of the HCS and the latitude of Ulysses are plotted at the time that a parcel of plasma emitted from the appropriate longitude would reach Ulysses. To aid comparison with Figure 1, the Carrington Rotation numbers corresponding to each data point are shown along the top of the figure. Beneath these, the letter S indicates that a magnetic field sector was observed and C indicates that a CME was observed during the rotation; all three CMEs were seen near longitudes where we might have expected to observe field sectors.

The figure shows that the reappearance of magnetic field

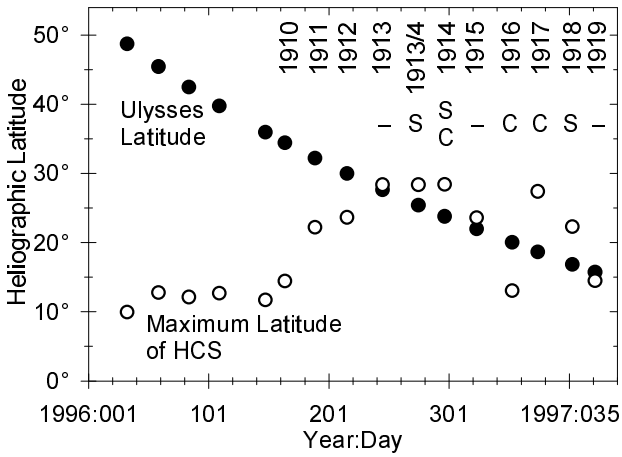

Figure 3. A comparison of the latitude of Ulysses with the maximum latitude of the HCS deduced from the neutral line at the source surface. The annotation is described in the text.

sector structure at Ulysses in September 1996 was a combination of the steadily reducing latitude of Ulysses and a rapid rise in the maximum latitude of the HCS deduced from the source surface maps. The rise started around June 1996 in the interval comparable with CR1910. In that comparable with CR1915 the predicted maximum HCS latitude drops again slightly and the lack of a clear sector at Ulysses is consistent with the spacecraft having a similar latitude. Skipping CR1916 and 1917 where the issue is confused by the CME signatures, we find that the sector in CR1918 is correctly predicted and also the absence in CR1919. Where sectors are observed at Ulysses, the estimated source longitude is consistent with the longitude of the maximum latitude of the neutral line. For CR1910-1915 this is within ±10° of 240° Carrington longitude. Thus, this study provides a further confirmation that the neutral line on the Stanford source surface maps provide a first order prediction of where HCS crossings will be observed by Ulysses. Preliminary comparisons with HCS maximum latitudes deduced from SOHO-LASCO synoptic maps [*Y.-M. Wang and R. A. Howard*, private communication] suggest lower maximum latitudes than obtained from the Stanford maps, but with least disagreement (~3°) in CR1913-1914 when Ulysses re-encountered the HCS, and thus not inconsistent with our observations. It is also noted that the alternative Stanford source surface maps, produced assuming the photospheric fields are purely radial and placing the source surface at 3.25 solar radii, also suggest lower maximum latitudes for the neutral line. However, these completely fail to predict the higher latitude Ulysses HCS crossings, most likely due to the source surface being set too high. This alternative model is apparently more successful at 1 AU near the ecliptic plane, and agreed better with the latitude of the first Ulysses southward crossing in 1993 [*Phillips et al.*, 1994].

Discussion

We have presented observations showing the reappearance of the magnetic field compressions associated with CIRs and the reappearance of magnetic field sector structure at Ulysses as the spacecraft returned from high northern latitudes. The maximum northern latitude reached by the HCS as observed by Ulysses on 30 Sept. 1996 was 25.5°N. This is a signifi-

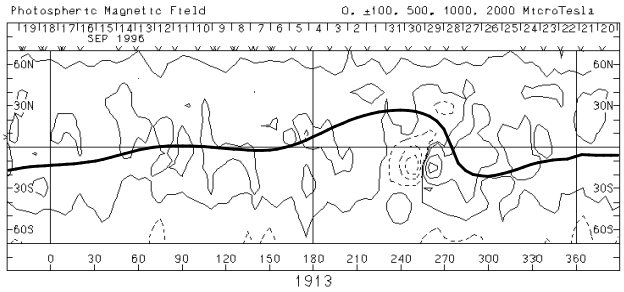

Figure 4. A Carrington map of the photospheric magnetic field observed by Wilcox Solar Observatory for Carrington Rotation 1913 . Note the bipolar signature of the active region near 240° longitude. The heavier overlaid black line shows the location of the neutral line at the source surface.

cantly higher latitude than that inferred from the Ulysses fast latitude scan observations in 1995, and given the lower solar activity in 1996 as discussed in the introduction, this higher maximum latitude is at first surprising. Thus it is interesting to ask what change in the photosphere and/or corona caused the latitude rise of the neutral line shown in Figure 3 and hence the reappearance of HCS crossings at Ulysses.

In an attempt to address this, Figure 4 shows a Carrington map of the photospheric magnetic field measured at WSO for CR1913. The solid lines represent contours of zero and increasingly positive (or outward) magnetic field strength and the dashed lines represent contours of increasingly negative (or inward) field strength. The map, derived from a sequence of full disk magnetograms, forms the inner boundary condition in the calculation of the source surface maps to which we compared the Ulysses HCS observations. The neutral line thus calculated for CR1913 at the 2.5 solar radii source surface has been overlaid on Figure 4 as a heavy black line. A strong bipolar feature, characteristic of an active region, is clear in the photospheric field at this time, in the longitude range 230-270°. It's negative polarity region is centred on 240° longitude and extends to high northern latitudes, consistent with the longitude where Ulysses observed negative polarity. Inspection of a sequence of these synoptic maps shows that this feature was present from CR1910 to CR1915, being most pronounced in 1912-14. The associated active region was visible in YOHKOH-SXT [*Solar Geophysical Data*, 1996] and SOHO EIT images [*B. J. Thomson*, private communication] over approximately the same period. Thus a reasonable interpretation would be that this long lived active region was responsible for producing the strong northward deflection of the HCS localised at Carrington longitude 240°, leading to its earlier and higher latitude than expected observation at Ulysses. This conclusion is supported by the recent coronal field modelling work of *Wang et al.*, [1997] based on SOHO-LASCO coronagraph observations from the same time period.

Following on from the interval discussed in this paper Ulysses is once again regularly observing HCS crossings as it nears the heliographic equator. In the subsequent years as solar activity begins to rise in cycle 23 and Ulysses begins its second passage to high southerly latitudes we will have further unique opportunities to study the relationship between HCS structure and solar activity.

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