Ulysses Observations of Changes in the Solar Polar Regions Around Solar Maximum

Geraint H. Jones and André Balogh

Abstract. During 2000-2001, the Ulysses spacecraft executed its second rapid pass from very high southern to very high northern heliolatitudes. Unlike the previous fast latitude scan, the recent one occurred near the maximum in solar activity. The solar magnetic field reversal, as evidenced by heliospheric magnetic field data, occurred between Ulysses's highest southern latitudes and highest northern latitudes. We examine the magnetic field structure of the solar polar regions by analyzing data returned by the magnetometer aboard Ulysses before and after the maximum southern and northern heliolatitude excursions. An attempt is made to infer the location of the heliospheric current sheet at high latitudes from these observations. The reversal of the magnetic field at the solar wind source surface is inferred to have occurred between November 2000 and August 2001, with the most likely time of reversal being early within that period.

INTRODUCTION

Since early 1992, the ESA/NASA Ulysses spacecraft has been in a 6.2-year near-polar orbit which takes it to maximum heliolatitudes of ± 80.2° (figure 1). The eccentricity of Ulysses's orbit leads to a very rapid scan around perihelion from high southern to high northern latitudes in only 10 months. Its first fast latitude scan occurred in 1994/1995, while approaching a minimum in the solar activity cycle. During 2000/2001, Ulysses repeated the scan, during a period coincident with solar maximum. The latter period has provided the first direct measurements of solar polar magnetic fields around the time of magnetic field polarity reversal. It is hoped that the data presented here will aid in the understanding of the polarity reversal process, and may help in the refinement of potential field models that depend on lower-latitude photospheric field measurements alone.

DATA ANALYSIS

The polarity of the heliographic magnetic field (HMF) at Ulysses was determined using standard techniques. With the use of SWOOPS plasma data [1], the instantaneous Parker spiral direction [2] was calculated from:

$$\phi = \arctan \left( \frac{(R_s - R_{hs}) \Omega \sin \theta}{v_{sw}} \right)$$

where $\theta=$colatitude, $\Omega=$solar rotation rate, $R_s=$heliocentric distance, $R_{hs}=$radius of solar wind source surface (taken to be 2.5 $R_{\odot}$), and $v_{sw}=$the solar wind velocity measured at Ulysses. The Carrington sidereal solar rotation period of 25.38 days was employed. Hourly averaged magnetic field data from Ulysses's magnetometer [3] were compared to the Parker spiral winding angle, and the polarity of the HMF determined from the angle between the actual azimuth angle and the Parker spiral angle. The source location of the solar wind was then estimated using standard ballistic mapping techniques. Heliolatitude was taken to be constant between the solar source surface and the spacecraft. The polarity of the solar wind source surface could then be estimated, either as being positive, i.e. outwards (here shown as white), or negative, i.e. inwards (grey). The timing of the departure of the plasma from the Sun was used to assign a Carrington rotation to the data values most relevant for later comparison with Earth-based observations.
FIGURE 1. The heliolatitude of Ulysses from launch to April 2002.

RESULTS

MAGNETIC POLARITY DISTRIBUTION OVERVIEW

The spatial distribution of source surface magnetic polarities estimated from Ulysses data is given in figures 2 and 3. Each of the eight views in the two figures shows the inferred HMF polarity mapped back to the solar wind source surface, looking down on the rotational poles. Northern hemisphere views are shown in the upper panels; southern hemisphere views in the lower panels. Each phase of the mission from equator to pole is shown, beginning with the first excursion to high southern latitudes after the Jovian encounter in early 1992. The dichotomy in magnetic polarity around solar minimum is clear, as shown by the almost uniform polarities in the two hemispheres to late 1997.

FIGURE 2. Polarity of the HMF at Ulysses, mapped back to the solar wind source surface. See text for description.
The short-lived high-latitude field reversals are not believed to be associated with the heliospheric current sheet, but rather with large-scale Alfvénic fluctuations in the magnetic field [4]. As expected, as solar maximum approached, this clear delineation of magnetic polarity by hemisphere was replaced by a far more complex mixture of the two polarities. As Ulysses ascended to high southern latitudes during 1998-2000, the "old" northern polarity (white) continued to be detected - this would become the "new" southern polarity.

The Southern Polar Region near Solar Maximum

Almost a full solar rotation was detected at maximum southern latitude during which the polarity remained that of the "old" southern polarity (grey) [5]. This suggests that Ulysses’s increasing latitude kept pace with the increase in inclination of the heliospheric current sheet (HCS) during the ascent to high southern latitudes, and then overtook the sheet near 80° south.

If the HCS remained a single, coherent structure without significant warps, this single-polarity solar rotation constrains the minimum time of polarity reversal at the solar wind source surface to the period at highest southern latitudes (~2000:323). However, although it is almost certain that the HCS inclination was near its maximum around then, only a small warp in the sheet would have been required to produce the observations described whilst most of the sheet had actually tipped past the south pole.

**FIGURE 3.** Polarity of the HMF at Ulysses, mapped back to the solar wind source surface. See text for description.
The Northern Polar Region near Solar Maximum

Northwards of heliolatitude ~67° north, from ~2001:236 onwards, there was little sign of the "old" northern polarity (white). On the return to lower latitudes, the sector structure may have been detected around 2002:018, at a heliolatitude of ~62° north. However, this possible sector was not clear, and it was two full solar rotations later when the first unambiguous sector structure was detected, at a heliolatitude of ~50° north. As the new northern polarity was clearly dominant at this time, this constrains the time of polarity reversal at the source surface to earlier than 2001:236. Quite striking is the shift in Carrington longitude covered most recently by the "new" southern polarity in the northern hemisphere. This is very different to the longitude range within which it was last seen during the ascent to high northern latitudes.

**SUMMARY**

The data presented here represent the first direct measurements of the solar polar magnetic fields at solar maximum. As expected, the polarity distribution was much more complex than that near solar minimum. There were few signs of non-dipolar field components during the solar maximum fast latitude scan. The polarity distribution detected by Ulysses indicates that the magnetic reversal in the solar wind source surface occurred between November 2000 and August 2001, and is likely to have been early within that time range. Refinements to the analysis techniques employed here continue to be made. Possible inadequacies in the use of ballistic mapping techniques are to be considered. The synthesis of the Ulysses data and in-ecliptic in-situ measurements from near-Earth and interplanetary spacecraft, and comet ion tail observations (e.g. [6]), will help construct a fuller picture of the inner heliosphere's structure around solar maximum.

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**REFERENCES**