Radial Heliospheric Magnetic Fields in Solar Wind Rarefaction Regions: Ulysses Observations

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Abstract. We examine the distribution of directions of the heliospheric magnetic field (HMF) measured by the Ulysses spacecraft during its mid-latitude transits of the heliosphere when it observed solar wind shears from the incursions of high-latitude fast solar wind toward the low-latitude slow solar wind. We look for nearly radial field orientations commonly observed in rarefaction regions (i.e. where the solar wind velocity decreases monotonically over several days). In contrast to CMEs where the HMF tends to be enhanced, the rarefaction regions with nearly radial magnetic fields tend to have extremely low magnetic field magnitude values. Within these rarefaction regions, there are “dwells” in the coronal source longitude of the measured solar wind in which the time dependence of the solar wind velocity is given to a very good approximation by \( V(t) = \frac{R}{t-t_0} \), where \( R \) is the heliocentric radial distance of the spacecraft. We have therefore compiled distributions within the dwells of the parameter \( \frac{|B_r|}{B} \) which is the cosine of the cone angle of the field from the radial direction. We study the mid-latitude transits that occurred during different phases of solar activity: 1992-1993 (decline), 1996-1997 (minimum), 2001-2002 (maximum), and 2005-2006 (decline). During three out of these four periods, the distributions of the HMF tended to be rather uniform in all HMF directions (\( 0 < \frac{|B_r|}{B} < 1 \)), but during 2001-2002, when the dwells were more frequent, the distributions tended more strongly toward \( \frac{|B_r|}{B} = 1 \). Such distributions were observed up to very high latitudes (65ºN). We discuss these observations in the context of the models proposed to explain the underwinding of the Parker spiral in terms of both a temporal variation in the coronal solar wind velocity and/or a longitudinal velocity gradient at the eastern edge of the solar wind source region. Only the latter can explain 26-day recurrent periods of radial magnetic field.

Keywords: Heliosphere; interplanetary magnetic field; solar wind plasma.

PACS: 96.50.Bh, 96.50.Ci, 96.50.Qx, 96.50.Wx

INTRODUCTION

During the Ulysses mid-latitude transits of the heliosphere, the spacecraft traversed regions of solar wind velocity shear between the low-latitude slow solar wind and the high-latitude fast solar wind. In these regions, quasi-recurrent rarefaction regions (where the solar wind velocity decreases monotonically over several days) were observed. Rarefaction regions usually exhibit heliospheric magnetic field (HMF) directions that deviate strongly from the Parker spiral direction, tending significantly more toward the radial direction (outward from or inward toward the Sun). This effect was first reported on Ulysses by Jones et al. [1], followed by Smith et al. [2], and examined in detail by Murphy et al. [3]. Competing explanations were offered by Schwadron [4] and Gosling and Skoug [5]. Schwadron and McComas [6] showed that such radial HMF orientations were a natural consequence of the east-west velocity shear in the solar wind rarefaction regions following the passage of a corotating interaction region (CIR) over the spacecraft. Thus, the radial HMF configuration should be a corotating structure and is a pure consequence of the basic mechanism of the HMF model proposed by Fisk [7]. On the other hand, Gosling and Skoug [5] and Riley and Gosling [8] showed that radial HMF orientations would occur in the solar wind rarefaction regions as a consequence of transient abrupt decreases in the solar wind speed at the corona that would be observed as a temporal evolving structure following the passage of fast transient disturbances (e.g. CMEs) over the spacecraft.

Solar wind rarefactions are easily identified in the Ulysses data by “dwells” in which the velocity (\( V \)) has an inverse dependence on time (\( t \)) and a direct dependence on the spacecraft helioradius (\( R \)) [9]. The coronal source of all of the solar wind within a dwell is restricted to a narrow range of solar longitudes at the eastern boundary of the coronal source of the high speed solar wind [9]. It then follows that the time dependence of the solar wind velocity is given to a
very good approximation by $V(t) = R/(t - t_0)$ as was confirmed by observations [10]. When $R/V$ is plotted versus time (in consistent units) dwells should show up as straight lines with a positive slope equal to unity. Here in this paper we first identify the dwells observed by Ulysses during its mid-latitude transits and then compile distributions of the HMF direction to compare them with the nominal Parker spiral direction. As a measure of the direction we follow [5] and compute the cosine of the radial cone angle $|B_r/B|$.

**FIGURE 1.** (a) Solar wind speed; (b) $R/V$ (in units of days); (c) magnetic field magnitude $B$; (d) $|B_r/B$; (e-f) magnetic field direction in the RTN coordinate system. The inclined red lines in Fig. 1(b) identify the dwells corresponding to $R/V \approx t$. The gray vertical bars indicate the time intervals when dwells were observed. The green arrows indicate the passage of CMEs as identified in [12].

**FIGURE 2.** Distributions of $|B_r/B|$ observed in selected dwells indicated in Fig. 1. The vertical short lines indicate the values of $|B_r/B|$ corresponding to the nominal Parker spiral at the location of Ulysses assuming a solar wind speed of 400 km s$^{-1}$ (red) and 800 km s$^{-1}$ (blue).

A useful diagnostic signature for periods of radial HMF, is the parameter $|B_r/B$ [5] which is the cosine of the cone angle of the field from the radial direction. Figure 1d shows that, although values of $|B_r/B$ can occur at any time, they are more likely to occur within dwells. We have compiled distributions of $|B_r/B$ within the dwells identified in Fig. 1. Figure 2 shows
that, for most of the rarefactions, the $|B_r|/B$ distributions extend right up to unity. The extreme cases are observed on days 3.5-8.5 of 1997 (analyzed in detail by Jones et al. [1]) and 289.0-293.5 of 1996 (corresponding to the passage of a CME with enhanced value of $B$). Cases with $|B_r|/B$ distributions not extending up to close to unity were observed on days 294.3-296.7 of 1996 (just after the passage of a CME) and on days 346.4-348.4 of 1996 (within the passage of a CME). The orientation of the flux rope with respect to the spacecraft determines the $|B_r|/B$ distribution observed within the CME.

Smith et al. [2] analyzed the HMF orientation averaged during all the corotating rarefaction regions observed between 30ºN and 10ºN shown in Fig. 1 and concluded that the HMF was underwound by ~30º with respect to the nominal Parker spiral.

**FIGURE 3.** The same as Fig. 1 but from day 300 of 2001 to day 365 of 2002.

**FIGURE 4.** The same as Fig. 2 but for selected dwells during the period 2001-2002.

Figure 3 shows, with the same format as Fig. 1, the period from day 300 of 2001 to day 365 of 2002. Although this period coincides with the solar maximum of solar cycle 23, the northern polar hole was already formed and during the northern polar passage Ulysses observed fast wind with a speed similar to that observed during the northern polar passage in 1996 during solar minimum [11]. Numerous dwells were observed throughout this solar maximum time interval but they did not follow any constant recurrent pattern. In general the dwells were more abundant than during the 1996-1997 period. Similarly to the period shown in Fig. 1, dwells coincide with rarefaction regions (Fig. 3a) and with periods of low magnetic field magnitude (Fig. 3c). The exceptions are the dwells that coincide with the passage of CMEs (such as on days 125-127 and 164-171 of 2002) when the field magnitude was enhanced.

Figure 4 shows, with the same format as Fig. 2, the $|B_r|/B$ distributions for selected dwells identified in Fig. 3. In general, the distributions tended more strongly toward $|B_r|/B \sim 1$ than in 1996-1997 (Fig. 2).
Such distributions were observed up to very high latitudes (~65°N).

CONCLUSIONS

We have scanned the Ulysses solar wind observations during two of its mid-latitude transits searching for dwells. These dwells are easily identifiable in plots of the parameter $R/T$ where they stand out as lines with slope=1. Because of the page limitation, for this preliminary report we have had to severely compress our data plots in Figs. 1 and 3. We realize the reader will not be able to verify our characterization of the trends in the figures until our full study is published. Although here we have shown only the periods 1996-1997 (coinciding with the minimum of solar cycle 22 and rising phase of solar cycle 23) and 2001-2002 (during the maximum of solar cycle 22), the other periods analyzed (i.e. 1992-1993 during the declining phase of solar cycle 22 and 2005-2006 during the declining phase of solar cycle 23) show similar series of dwells and rarefaction regions as in 1996-1997 appearing in a 26-day recurrent pattern. In contrast, the series of dwells in 2001-2002 did not show any recurrent character. The $|B_r|/B$ distributions during the solar minimum periods tend to be rather uniform in all HMF directions ($0<|B_r|/B<1$) with a trend for HMF directions to be more radial that the nominal Parker spiral. By contrast, the $|B_r|/B$ distributions during the solar maximum time interval tend more strongly toward $|B_r|/B~1$.

In order to explain the underwinding of the Parker spiral in rarefaction regions two alternative explanations have been proposed. Schwadron [4] and Schwadron and McComas [6] built upon the idea of Fisk [7] that strongly underwound intervals within rarefaction regions result from the eastward motion of magnetic footpoints on the Sun, including also the effects associated with speed decreases on those field lines as they cross the trailing edges of coronal holes. The essence of their argument is that the motion of these foot points across the trailing boundaries is facilitated by interchange reconnection of open and closed field lines. Moreover, they suggested that the interchange reconnection produces a drop in speed on the newly reconnected field. They argued that this process could be approximated (at some sufficiently large height in the corona) by an eastward-azimuthal motion of field lines in a fixed pattern of high and low-speed solar wind outflow. On the other hand, Gosling and Skoug [5] proposed that the radial fields in rarefaction regions are produced by a sudden abrupt decrease in the solar wind velocity simultaneously on a particular longitudinal range of field lines at or near the solar source surface. Therefore, whereas the model of Schwadron [4] seeks to explain underwound fields that recur from one rotation to the next, the model of Gosling and Skoug [5] addresses the near-radial fields of transient nature that do not appear on subsequent solar rotations. Therefore, the recurrent character of the dwells observed during the solar minimum periods indicates a spatial structure as the origin of the dwells and near-radial fields, whereas during solar maximum a mix of spatial and transient structures may be responsible for the observed underwound field.

As a summary, we have shown that:

- Mid-latitude solar wind rarefaction regions:
  - coincide with “dwells” (i.e. solar wind originated at approximately the same longitude),
  - show low magnetic field magnitude, and
  - show non-Parker (more radial) magnetic field orientations.

- During the periods 1992-93, 1996-97, and part of 2005-06, rarefaction regions appear in 26-day recurrent series (unlikely if they result from transient drops in speed at the solar source).

- During solar maximum (2001-2002) rarefaction regions are more frequent and with HMF distributions more focused around $|B_r|/B~1$. A mix of coronal hole recurrences and transients either in the solar wind source or in the coronal hole evolution are observed.

ACKNOWLEDGMENTS

We acknowledge the Ulysses Data System (UDS) for providing the data used in this work.

REFERENCES