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The North-South Asymmetry of the Heliospheric Current Sheet: Results of an MHD Simulation

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Abstract. A displacement of the heliospheric current sheet (HCS) south of the helioequator by ~10° was proposed by Simpson et al. (1996) as a possible explanation of the north-south asymmetry in the galactic cosmic rays observed by Ulysses during its first fast transit in 1994-1995. The idea was not supported by magnetic field measurements on Ulysses and, on this ground, was dismissed by Simpson et al. (1996). In addition, Erdös & Balogh (1998) argued that any north-south symmetry was unlikely as there should be flux balance between the magnetic sectors of opposite polarity. Nonetheless, many in the scientific community have accepted the original suggestion of Simpson et al. (1996) that a displacement of the HCS was responsible for the cosmic ray asymmetry. In this paper, using a magnetohydrodynamic model of the solar corona and solar wind that includes both dipole and quadrupole magnetic source terms, we show that a north-south asymmetry of the magnetic field on the Sun does not give rise to a displacement of the HCS. The lack of displacement of the HCS results from a latitudinal redistribution of magnetic flux near the Sun where the plasma $\beta \ll 1$. The latitudinal redistribution is a direct consequence of the magnetic field gradient between pole and equator. Near the Sun, the latitudinal gradient in magnetic field generates meridional flows directed equatorward that tend to relax the gradient in the magnetic field (to make it more latitude-independent) as heliocentric distance increases. If there is an asymmetry between north and south magnetic field strength then the meridional flows are also asymmetric (i.e., stronger in the hemisphere of stronger magnetic field). Because the magnetic fluxes (positive and negative) in the hemispheres must be equal, the redistribution shifts the HCS in the direction of the hemisphere with a weaker field and brings the field strength on both sides of the HCS into balance by ~16 $R_\odot$. At larger distances, where the magnetic field is relatively weak ($\beta \gg 1$), the HCS can be displaced if there is a difference in total pressure between the hemispheres.

1. Introduction

The apparent displacement of the symmetry plane of the cosmic-ray nuclei and anomalous helium by ~10° south of the heliographic equator was a surprising result of Ulysses observations during its first fast latitude transit from -80° to +80° in heliographic latitude in 1994-1995 (Simpson et al. 1996). In contrast to the cosmic ray flux, the radial magnetic field observed concurrently by Ulysses was largely north-south symmetric (Smith & Balogh 1995; Smith et al. 1995; Forsyth et al. 1996), which led Simpson et al. (1996) to dismiss the idea that the displacement or "coning" of the HCS was the cause of the asymmetry in the cosmic ray modulation and to conclude that the "cosmic-ray intensity offset is not a local phenomenon". Nevertheless, the idea that the asymmetry in the cosmic ray fluxes reflected an asymmetry in the heliospheric magnetic field gained acceptance in the scientific community.

This interpretation appeared to be supported by observations of the solar magnetic field taken at the Wilcox Solar Observatory that indicated that the magnetic field strength within the polar caps of the Sun was, indeed, significantly different during the Ulysses transit: the southern polar field was noticeably stronger than the northern polar field (Smith et al. 2000). These data led Smith et al. (2000) to suggest that the symmetry of the heliospheric magnetic field in Ulysses observation might be a coincidence resulting from Ulysses' movement in latitude together with temporal changes in the polar fields.

Mursula & Hiltula (2003) plotted the polarity of the heliospheric magnetic field as observed at 1 AU separately for fall and spring seasons (when Earth is located, respectively, above and below the helioequator) from 1965 to 2001. They noted that the correspondence of the polarity to the Sun's polar field in the hemisphere of Earth's excursion (the Rosenberg & Coleman (1969) effect) was more prominent during fall seasons. Mursula & Hiltula (2003) suggested that this asymmetry indicated that the southward shift of the HCS was a persistent pattern. However, the estimated magnitude of the shift they found was only "a few degrees," i.e., much smaller than the shift needed to explain the cosmic ray asymmetry observed by Ulysses.

Erdös & Balogh (1998) noted that any north-south asymmetry in the sector structure was unlikely because of the requirement of flux balance between sectors with opposite polarities and the observed heliolatitude independence of the radial magnetic field as observed by Ulysses during its first latitude transit. More recently, Erdös & Balogh (2010) extended their analysis to Ulysses' 3rd fast transit in 2006 and concluded that "a southward displacement of the HCS by 2-3° is possible." Virtanen & Mursula (2010) arrived at a similar conclusion. Although none of the authors indicated a statistical error of the estimated displacement, it appears to be small compared with the observed asymmetry of the cosmic rays.

During solar minimum, one can approximate the Sun's magnetic field as a dipole nearly aligned with the solar rotation axis. The HCS is correspondingly aligned with the helioequatorial plane (e.g., Hoeksema & Scherrer 1986; Sanderson et al. 2003). Higher harmonics are typically small, but a quadrupole contribution can be significant and has been considered as a source of the north-south asymmetry (see, e.g., Osherovich et al. 1999; Bravo & González-Esparza 2000; Mursula & Hiltula 2004).

In this paper, we simulate the observed north-south asymmetry of the solar magnetic field using a superposition of dipole and quadrupole contributions. We then use a magnetohydrodynamic model of the solar corona and solar wind to compute the plasma and magnetic field parameters from the coronal base out to 100 AU. We show that the asymmetry that results from the quadrupole contribution does not produce an offset of the HCS. Near the Sun, where the plasma β (the ratio of thermal and magnetic pressure) is $\ll 1$, the latitudinal redistribution of magnetic flux by meridional flows eliminates the displacement of the HCS and brings the magnetic field strength on both sides of the HCS into balance by $\sim 16\ R_\odot$, where $R_\odot$ is the solar radius. At larger distances, where the magnetic field is relatively weak ($\beta \gg 1$), the HCS can still deviate from the helioequator if the total pressure in the hemispheres is different, but any such offset is small.

2. Simulation Model

We use the numerical three-dimensional model of the solar corona and solar wind described in Usmanov (1996); Usmanov et al. (2000); Usmanov & Goldstein (2003); Usmanov et al. (2012). In the most recent version of that model, the computational domain is divided into three sub-regions: the inner or "coronal" region that extends from the coronal base to 20 $R_{\odot}$, the "intermediate" region from 20 $R_{\odot}$ to 0.3 AU, and the "outer" region from 0.3 to 100 AU. The governing equations in the inner and intermediate regions include the usual set of mass, momentum, magnetic induction, and energy conservation equations coupled with an evolution equation for the energy density of Alfvén waves in the WKB approximation (Jacques 1978; Usmanov 1996; Usmanov et al. 2000; Usmanov & Goldstein 2003). In the outer region, the mean-field solar-wind equations that account for pickup proton effects and turbulent heating are solved simultaneously with turbulence transport equations (Usmanov et al. 2009, 2011, 2012). We obtain steady-state solutions in the frame of reference rotating with the Sun using the time relaxation method in the inner and outer regions and a forward integration along the radial coordinate in the intermediate region. We use the third-order Central Weighted Essentially Non-Oscillatory (CWENO) numerical scheme (Kurganov & Levy 2000) in combination with a Runge-Kutta third-order time discretization (Gottlieb et al. 2001).

We take the boundary conditions at the coronal base to be axisymmetric with a magnetic field consisting of both a dipole and a quadrupole aligned with the rotation axis of the Sun. The intensity of the dipole is set by the value of the radial field on Sun's poles of 13 G and the quadrupole contribution is specified to make the field strongly asymmetric so that the northern field is 1/3 the strength of the southern field (8 and 23.5 G, respectively). The neutral line is correspondingly shifted southward by $\Delta\theta \sim 15°$. The reader is referred to Usmanov et al. (2012) for a description of the other boundary conditions and model parameters.

3. Simulation Results

Figure 1 shows radial profiles of the radial magnetic field B_r, which defines the sector structure and dominates over other components in the inner heliosphere, at a number of heliocentric distances from 1 to 215 $R_{\odot}$ (1 AU). The initially strongly asymmetric (with respect to the equatorial plane) profile (Figure 1a) becomes increasingly symmetric as heliocentric distance increases (Figure 1b–1d) and is virtually symmetric by $r = 32\ R_{\odot}$ (Figure 1e–1f). The latitudinal offset $\Delta\theta$ of the neutral line decreases even faster and disappears by $r = 16\ R_{\odot}$. Note that beyond 32 $R_{\odot}$, the magnetic field is only weakly dependent of latitude (except for the region around the heliospheric current sheet where B_r changes polarity) in agreement with the Ulysses observations that found no evidence of a significant latitudinal gradient in B_r (Smith & Balogh 1995).

In Figure 2 we show a contour plot of plasma and magnetic field parameters in the meridional plane in the inner region 1-20 $R_{\odot}$. While the distributions of radial (u_r) and meridional (u_θ) velocities are significantly asymmetric about the equatorial plane, the magnetic field parameters B and $r^2 B_r$ become more symmetric and the neutral line (the heavy blue line in Figure 2d) approaches the helioequator as the distance increases. Obviously, the redistribution of magnetic flux is associated with the meridional flows generated by the equatorward gradients of magnetic pressure. Because the magnetic

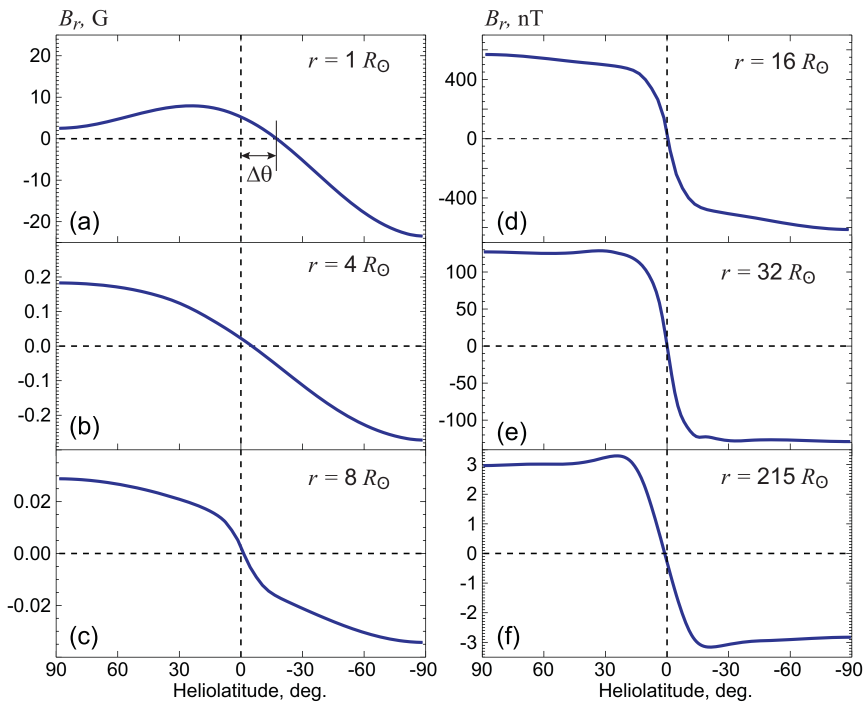

Figure 1. Latitudinal profiles of the radial magnetic field B_r at heliocentric distances r = 1, 4, 8, 16, 32, and 215 $R_\odot$. $\Delta\theta$ is the latitudinal offset of the neutral line.

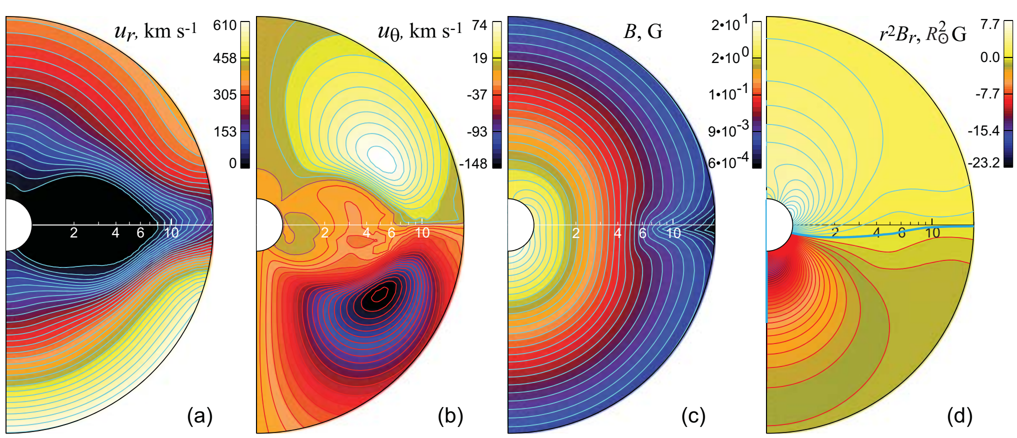

Figure 2. Contour plots of (a) the radial velocity u_r, (b) meridional velocity u_θ, (c) magnetic field magnitude B, and (d) radial magnetic field B_r scaled as r^2 in the meridional plane from 1 to 20 $R_\odot$. The heavy blue line in (d) is the neutral line.

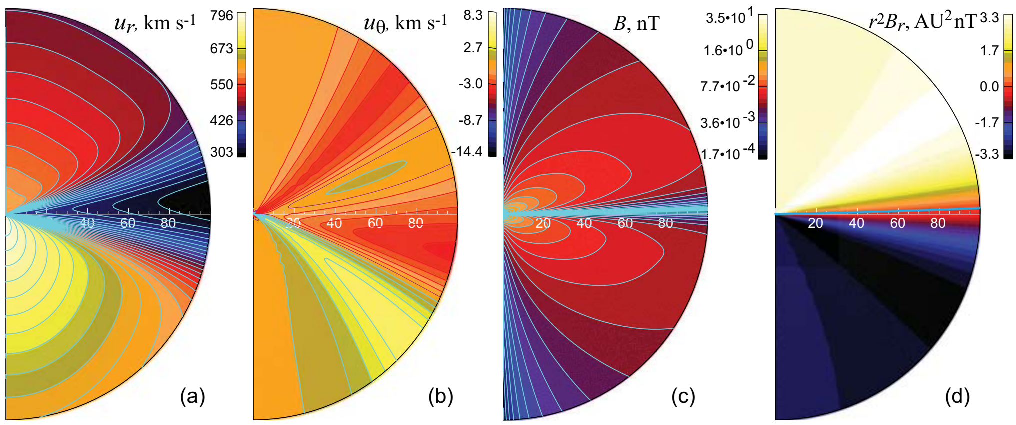

Figure 3. Contour plots in the meridional plant of (a) the radial velocity u_r, (b) meridional velocity u_θ, (c) magnetic field magnitude B, and (d) radial magnetic field B_r scaled as r^2 in the region from 0.3 to 100 AU. The heavy blue line in (d) is the neutral line.

field and its gradient are larger in the southern hemisphere, the equatorward flows in that hemisphere are correspondingly stronger. The latitudinal redistribution of magnetic flux in the solar corona and solar wind has been discussed by Suess & Smith (1996); Suess et al. (1996); Usmanov et al. (2000) in the context of the lack of a significant latitude gradient in the radial magnetic field as observed by Ulysses.

Figure 3 shows same parameters as in Figure 2 in the outer region from 0.3 to 100 AU. Unlike the inner region, where B is defined mostly by B_r (Figure 2c), the dominant component outside of 1 AU is the azimuthal field B_ϕ. The pattern of meridional velocities in the outer region is also significantly different due to the interplay of forces in the meridional direction (see Usmanov et al. 2000). The solar wind flow is notably asymmetric about the equatorial plane with lower velocities in the northern hemisphere. Correspondingly, the magnetic field winding and the field itself are stronger in this hemisphere and the neutral line deviates northward from the helioequator by several degrees. Even in the present case of a highly asymmetric field at the Sun, the deviation of the neutral line from the helioequator is still relatively small.

4. Conclusions

We have presented simulation results from a magnetohydrodynamic solar wind model with a magnetic field on the Sun composed of a dipole and a quadrupole. The quadrupole contribution is a source of north-south asymmetry and we studied how the asymmetry maps into the heliosphere. We have shown that

(1) The north-south asymmetry of Sun's magnetic field is not translated directly into an asymmetry of the heliospheric magnetic field.

(2) The latitudinal flows redistribute magnetic flux in latitude. This leads to a relaxation of latitudinal gradients in the magnetic field, except for a relatively narrow band where those gradients are concentrated (the heliospheric current sheet). This effect was observed by Ulysses.

(3) Near the Sun, where plasma $\beta \ll 1$, the meridional redistribution of magnetic flux eliminates the north-south asymmetry so that the magnetic field strengths on both sides of the HCS come into balance by ~16 $R_\odot$.

(4) At larger distances, where the magnetic field is relatively weak ($\beta \gg 1$), the HCS can be displaced due to differences in total pressure between the hemispheres. Although a displacement of "a few degrees" appears to be possible, one of order 10° is unlikely.

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