Heliospheric Current Sheet Distortions from Adjacent Outflowing Transients: Multi-spacecraft Observations

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Abstract. The heliospheric current sheet (HCS) is a permanent solar wind feature, with well predicted Earth passages, but it can be structured and its main orientation can be highly distorted. We report new observations from 2 spacecraft in the solar wind (supported by observations from 3 spacecraft in the nightside magnetosheath), showing an evolution across the Sun-Earth line of large field reversals adjacent to the HCS. Contrary to a previously reported multi-spacecraft event, this case shows that the field inversion structure cannot be assumed to be well preserved and close to planar on the scale of the magnetospheric cross-section. However, both cases indicate the presence of field reversals in an away sector that is connected to the southern solar magnetic hemisphere but lies unexpectedly above a toward sector. Following the interpretation of the reversals as transient outflowing loops, associated initial flow deviations can be envisaged to account for the HCS deformations.

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INTRODUCTION

With its main normal generally tilted with respect to the ecliptic plane, the HCS is one example of solar wind feature, that impacts the near Earth environment, interacting with the Earth's bow shock and magnetosphere. Despite possible local distortions of the sector boundary [1, 2], the HCS passage near Earth is a relatively well predicted recurring phenomenon [*e.g.*, 3], unlike any other solar event (*e.g.*, CME, flare). In the present minimum period of solar activity, the toward sector (sunward IMF) is connected to the northern solar magnetic hemisphere, and the away sector (anti-sunward IMF) to the southern hemisphere. At the same time, it is common to observe multiple current sheet crossings near the HCS, which may be caused by adjacent transient outflowing loops formed as a result of interchange reconnection [4, 2]. As reported for an away-to-toward sector crossing on 2007 March 4, multi-spacecraft observations show flow accelerations within the apparent layered structure, which disappear at the largest distance from the Sun [2]. This event suggests (1) that outflowing loops in the away sector are the cause for the anomalous inclination of that sector above the toward sector and (2) that the apparent layered structure of the HCS could be recognised as a useful marker for magnetospheric studies, since the HCS field inversion structure remains relatively steady as it is convected between separate positions close to the Sun-Earth line from L1 to the distant tail [2]. Here we present another set of multi-spacecraft observations to further test the above two premises.

OBSERVATIONS

We study the toward-to-away sector crossing of 2005 June 27 near Earth (between 19 and 23 UT). Figure 1 presents GSE positions of spacecraft present during this period in the solar wind and magnetosheath. *Wind* and the Advanced Composition Explorer (ACE) are near the L1 Lagrangian point, with *Wind* 55 R_E duskward and ACE 41 R_E dawnward of the Sun-Earth line. While *Geotail* samples the magnetosheath on the dusk side, *Double Star* TC-1 and *Cluster* are near the dawn flank. TC-1 and *Cluster* sample the magnetosheath, more or less intermittently, when the increased dynamic pressure associated with the high-density plasma sheet drives the magnetopause inward. Figure 1 also gives plane projections of normals to the solar wind field reversals, as obtained and discussed below.

Figures 2 and 3 give an overview of the sector crossing near L1 for the same 3 hour interval (between 19 and 22 UT) at *Wind* and ACE respectively. Panels (a-b) show respectively the magnetic field strength and Cartesian GSE components. The polarity turns from a toward (*i.e.*, inward, $B_x > 0$) to away (*i.e.*, outward, $B_x < 0$) IMF sector polarity. The sector boundary, characterised by its associated lower $|\mathbf{B}|$, appears layered, with between three to four major magnetic field reversals at localised current sheets, depending on the spacecraft. They are best identified through their changes in B_x and B_y. Each discontinuity at *Wind* (ACE) is indicated by a blue vertical line and denoted alphabetically (primed) with time. The sector crossing is a large-scale phenomenon seen also

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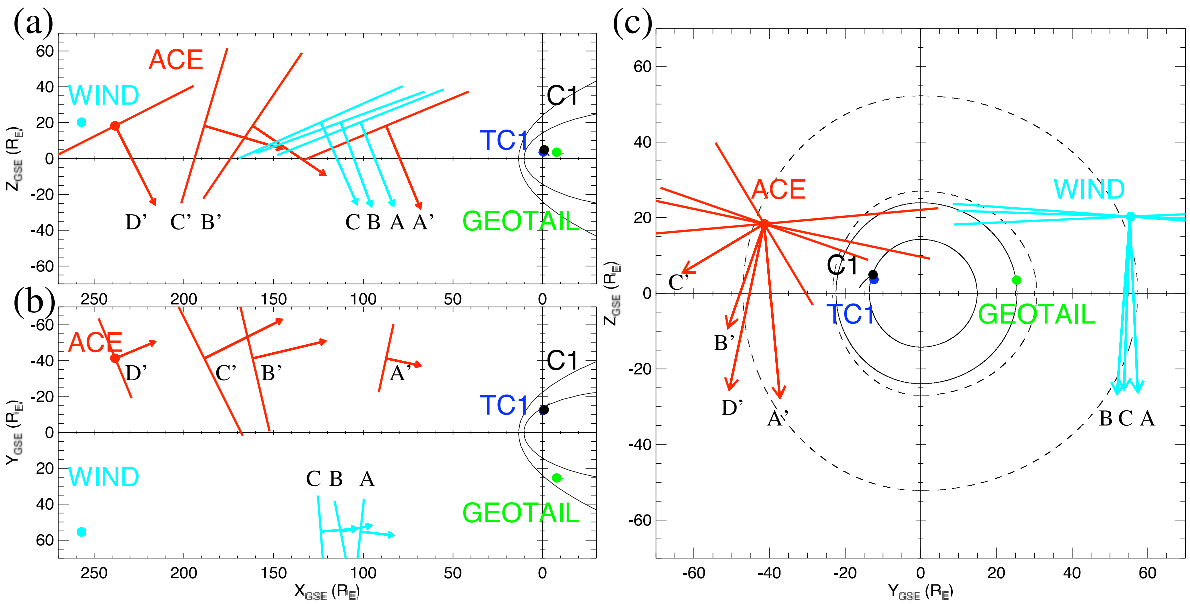

FIGURE 1. Spacecraft positions and discontinuity normals during the passage of the HCS near Earth on 2005 June 27, in the (a) $X-Z$, (b) $X-Y$ and (c) $Y-Z$ GSE planes. The discontinuity normals are shown at spacecraft positions shifted earthward along the Sun-Earth line, with respect to the positions at the passage time of the last discontinuity, D’ (at ACE). A solar wind pressure of 2.7 nPa and an IMF B_z of 0 nT were used to compute the GSE aberrated magnetopause [5] and bow shock [6] models. In the right panel they are represented by plain contours at $X_{GSE} = 0$ $\mathrm{R_E}$ and dashed contours at $X_{GSE} = -10$ $\mathrm{R_E}$.

by *Geotail*, TC-1 and Cluster in the magnetosheath (not shown). We have searched for field reversals in the magnetosheath similar to the ones found in the solar wind, but their detection is complicated by the presence of magnetic pulsations, akin to noise.

Until the passage of the layered structure, the IMF lies in the equatorial plane (with B_z near 0, in panel b), but points slightly away from this equatorial orientation and in opposite directions between spacecraft in the solar wind: at *Wind*, the IMF points slightly northward ($B_z \sim 1.5$ nT at 19:30 UT), while at ACE, it is directed more southward ($B_z \sim -1$ nT at 19:45 UT) and turns northward at the passage of the first reversal, A’. The IMF directions are similar between *Wind* and ACE after A-A’, ruling out any offset between instruments. The sign change in B_z is also seen in the dusk magnetosheath at *Geotail* (not shown). This indicates that the solar wind conditions affecting the Earth’s environment are best represented by the measurements at ACE.

The sector crossing occurs within a heat flux dropout (HFD) encompassing the interval shown. The suprathermal electron phase space distributions in panels (c) do not allow the clear detection of the true sector boundary (TSB), which would be expected to be seen in a pitch angle (PA) flip of the residual strahl population, here from 180 to 0°. At *Wind*, the reasons for this are the low temporal and angular data resolutions and the presence of counterstreaming electrons predominant downstream of A, but the PA transition is visible progressively over the 3 hour interval. At ACE, the apparent counterstreaming is most likely due to depletions of plasma at 90°PA [7] (as it could be at *Wind* as well), possibly over unequal field-aligned halo populations [8]. However, between discontinuities A and B, the HFD is deeper, revealing a dominant residual beam at PA near 0°. This suggests that the TSB may be located at discontinuity A’ or downstream of A’. In the simplest case, the TSB is co-located with the major magnetic field reversal at the HCS, thus pointing to the first discontinuity A’ as the main HCS.

Panels (d) show the ion (or proton depending on the mission) bulk flow speed V ($|\mathbf{V}|$). The solar wind speeds range between 410 to 380 $\mathrm{km\,s^{-1}}$, decreasing slightly during the sector crossing and without any substantial accelerations associated with the field reversals. For an average at ACE and *Wind*, the value between the field reversals is $V_{SW} = 400$ $\mathrm{km\,s^{-1}}$.

ANALYSIS AND DISCUSSION

We perform a minimum variance analysis (MVA) on the magnetic field data for each discontinuity in the solar wind. The resulting MVA directions, the normals to the solar wind current sheets at the centre of the field reversal (consistent with a cross-product analysis), are given in Table 1 and projected on the different GSE planes in

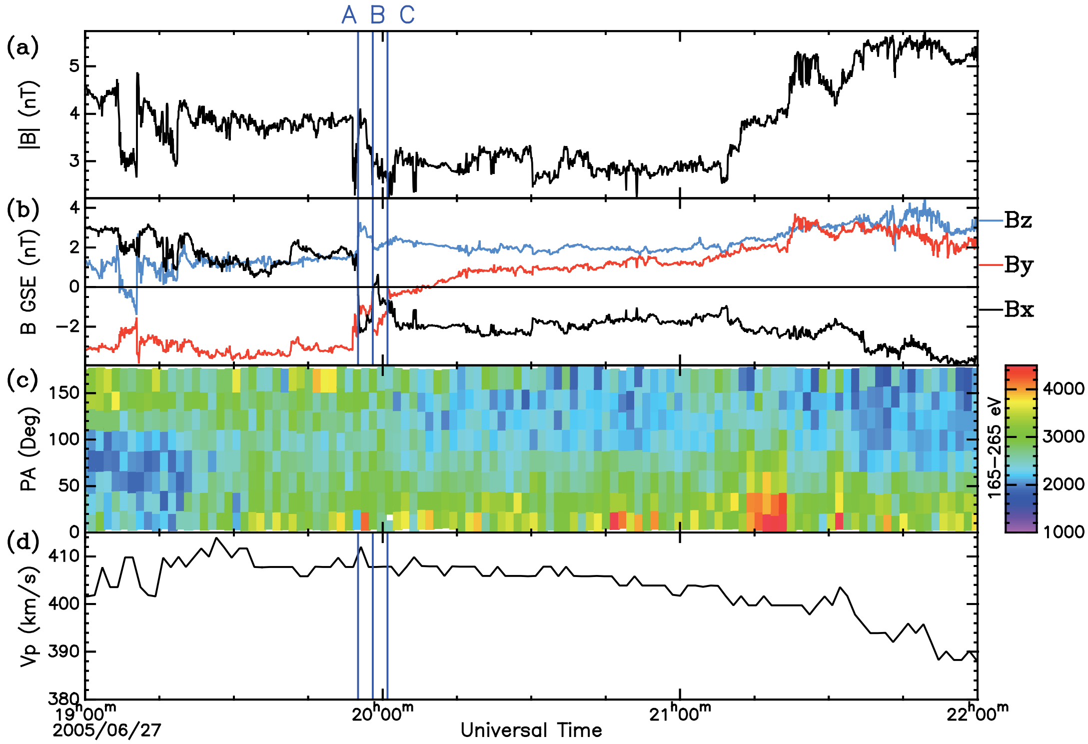

FIGURE 2. The sector boundary crossing observed on 2005 June 27 by *Wind*. The plot shows (a) the total and (b) the Cartesian GSE components of the magnetic field, (c) the colour-coded PA velocity distributions f(v) of suprathermal electrons, in units of s^3 cm^6 and (d) the plasma bulk flow speed. Magnetic discontinuities, A, B and C, are indicated by vertical lines.

Figure 1, pointing in the downstream direction by convention. The spacecraft positions are shifted earthward along the Sun-Earth line, with respect to the positions at the time of the last recorded discontinuity, D', based on the values of V_{SW} and the time duration between the discontinuity arrivals. In this reference frame, there is a good correspondence between first discontinuities A and A' in their alignment across the Sun-Earth line and in their orientation. Another characteristic common to A and A' is that they are the discontinuities with the largest changes in B_x. The following discontinuities (upstream of A-A') do not align so well across the Sun-Earth line.

TABLE 1. MVA results for the magnetic discontinuities in the sector crossing of 2005 June 27. From left to right are the spacecraft concerned, the crossing time, the discontinuity name and the obtained normal vector **N**.

S/C	Time	Dis.	**N** (GSE)
Wind	19:55:04	A	[-0.368, 0.041, -0.929]
	19:58:01	B	[-0.343, -0.067, -0.937]
	20:00:58	C	[-0.404, -0.031, -0.914]
ACE	20:10:01	A'	[-0.381, -0.082, -0.920]
	20:30:31	B'	[-0.813, -0.191, -0.550]
	20:37:40	C'	[-0.865, -0.430, -0.257]
	20:50:52	D'	[-0.444, -0.185, -0.876]

The above results indicate that the first discontinuity A-A' identified as the main HCS is a steady structure, followed by field reversals in the away sector. Following the interpretation of those field reversals as quasi-steady outflows of quiet loops embedded in the sector structure [4, 2], they display an evolution across the Sun-Earth line. An outflow direction from West to East (dawn to dusk) is consistent with the B_z changes that are similar between ACE and *Geotail*. We may be following the evolution of a bunch of loops with variable properties [2]. Here the large size differences of the structures between spacecraft (A-C versus A'-D', see Figure 1b) suggest that the transients at ACE are spatially different than the ones at *Wind*, the ACE transients possibly following the track of the *Wind* transients from West to East along the sector boundary. In this case, the apparent layered structure of the HCS, as it convects in the solar wind, cannot be assumed to be close to planar on the scale of the magnetospheric cross-section.

Furthermore, the southward orientation of the normal direction to the HCS (pointing downstream, Figure 1a) indicates a toward sector lying below an away sector, in apparent contradiction with the global heliospheric magnetic configuration. The intersection of A-A' with the ecliptic plane (Figure 1b) is aligned in a direction 35 to

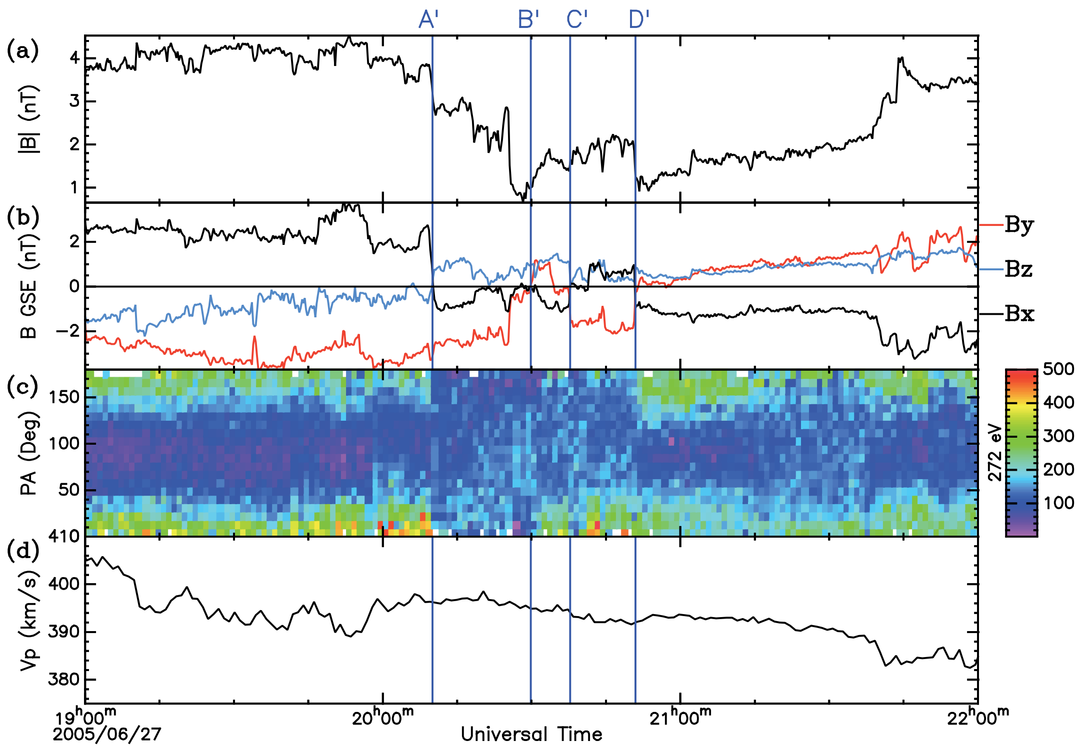

FIGURE 3. The sector boundary crossing observed on 2005 June 27 by ACE, with panels as in Figure 2 and magnetic discontinuities, A', B', C' and D', indicated by vertical lines.

45° larger than the 45°-angle expected near Earth's orbit. Finally, in the plane across the Sun-Earth line (Figure 1c), a discrepancy angle of ∼ 90° exists between observations of A-A' at L1 and models near 1 AU, constructed from solar magnetograms (in Carrington rotation 2031, see, *e.g.*, runs from the Community Coordinated Modeling Center, CCMC).

The multi-spacecraft observations presented here show a highly distorted HCS (slightly tilted with respect to the ecliptic and with sector polarities opposite to those expected) and an evolution of large field reversals adjacent to the HCS, in this case from West to East. This 2005 event and the 2007 event reported in [2] are two complementary sector crossings during the present solar minimum, which both illustrate an away sector inclined above a toward sector. This may be linked to the southward displacement of the HCS reported during previous solar minima (also known as the 'bashful ballerina') [*e.g.*, 9, 10, 11], *e.g.* outflows in the distorted locus may lead to deflections in the regions, pinned down below, that have the expected sector polarities. Yet, in the present event, there is no substantially accelerated plasma associated with the field reversals (contrary to the 2007 event). Since the HFD may indicate electron scattering on loop field lines which have reached large heliospheric distances [12], the extent of the HFD may well reflect the number and age of the transients channelled along the sector boundary. Thus, it is possible to envisage that associated flow deviations presumably present initially could account for the highly-inclined orientation of the away sector (with transients) above the toward sector.

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