Coincidence of heliospheric current sheet and stream interface: Implications for the origin and evolution of the solar wind

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Abstract In general, the heliospheric current sheet (HCS), which defines the boundary of sunward and antisunward magnetic field, is encased by the slow solar wind. The stream interface (SI) represents the boundary between the solar wind plasmas of different origin and/or characteristics. According to earlier studies using data of low time resolution, the SI and HCS get closer further away from the Sun, and the two structures coincide with each other around 5 AU. In this study, we use STEREO data of a much higher time resolution to reveal an unusual case where the SI and HCS are coincident near 1 AU and separated from the so-called true sector boundary (TSB) at which the suprathermal electrons change their relative propagation directions. Preliminary analysis suggests that the closed loops in pseudostreamers continually have interchange reconnection with the open-field lines that lead them, resulting not only in the coincidence of HCS and SI but also in the separation of the TSB from the HCS/SI. We therefore conclude that the interchange reconnection plays an important role in the evolution of slow solar wind.

1. Introduction

Solar wind is generally classified as “fast” (v ≥ 550 km s⁻¹) and “slow” solar wind (v ≤ 450 km s⁻¹), which differ in their physical nature and regions of origin [e.g., Wang et al., 2000]. In addition to differences in speed, their proton densities, proton temperatures, helium abundances, and “freeze-in” temperatures are also distinct from each other [Bame et al., 1977; Borini et al., 1981; Freeman and Lopez, 1985; Geiss et al., 1995]. Fast solar wind is believed to originate from coronal holes, the open-field regions and highly diverging coronal structures [Zirker, 1977; Zhao, 2011]. However, the origin of slow solar wind is still not well understood [Edmondson et al., 2009; Zhao, 2011]. Closed field regions, especially the helmet streamers, are one most likely origin of the slow solar wind [e.g., Hundhausen, 1977; Feldman et al., 1981]. Recent studies show that outward moving plasma “blobs” and flows from pseudostreamers could be important portions of slow solar wind [Wang et al., 2000, 2007; Liu et al., 2010; Owens et al., 2014; Crooker et al., 2014].

Compression interaction regions will form when fast solar wind overtakes slow solar wind. If these structures are roughly time stationary and can be recurrently observed, these regions are called corotating interaction regions (CIRs) [e.g., Gosling and Pizzo, 1999; Lee, 2000]. Inside a CIR, there lies at least one stream interface (SI), which separates the slow and fast solar wind [Crooker et al., 1999]. Composition analysis of Ulysses data by Wimmer-Schweingruber et al. [1997] shows multiple SIs in a single CIR. Crooker et al. [1999] summarized nine criteria to identify SIs, including both the compositional characteristics and other signatures, such as a drop in density, a rise in temperature, and a flow shear. A pair of shocks also forms to surround a CIR with a forward shock propagating into the slow solar wind in the leading edge and a reverse shock propagating back into the fast solar wind in the trailing edge [Gosling and Pizzo, 1999]. CIR shocks are usually well formed beyond 1 AU, and pressure waves are frequently observed within 1 AU [Gosling et al., 1976; Hundhausen and Gosling, 1976; Steinberg et al., 2005]. Nevertheless, Jian et al. [2006] found CIR shocks near 0.72 AU. A recent study shows that shocks of a CIR pair could accelerate particles between the two CIRs near 1 AU [Wu et al., 2014].

The heliospheric current sheet (HCS) is defined as a current layer that forms where the interplanetary magnetic field (IMF) changes polarity [Crooker et al., 2004; Liu et al., 2014], usually encompassed by slow solar wind. Suprathermal electrons emitted from the Sun travel along the magnetic field lines due to their large scattering mean free paths, forming strahls around pitch angle 0° (180°) when the magnetic field lines are directed antisunward (sunward) [Lavraud et al., 2010]. The place where the suprathermal electron strahls
change pitch angle is called true sector boundary (TSB). Ideally, the HCS coincides with the TSB, forming the boundary that separates two solar sectors of different IMF polarities [e.g., Kahler et al., 1996, 2003; Foullon et al., 2009; Liu et al., 2014]; however, there are complications. The study of Foullon et al. [2009] revealed the multilayer features of some HCSs. McComas et al. [1989] first put forward the concept of heat flux dropouts (HFDs), where suprathermal electron strahls disappeared. They suggested that HFDs are a signature for magnetic reconnection, while more recent studies indicate that HFDs could be the result of pitch angle scattering, possibly caused by particle-wave interactions [Crooker et al., 2003; Pagel et al., 2005]. In addition, in some cases a mismatch between HCSs and TS Bs has been found [Crooker et al., 1996, 2004]. These cases are special because the suprathermal electron strahls flow sunward, which is not the expected direction, during these intervals. Kahler et al. [1996, 2003] suggested that the turned back flux tubes could show such reversal polarity signature. Crooker et al. [2004] analyzed eight cases observed during 1994–1995 and found that interchange reconnection may play a crucial role in forming the inverted magnetic field lines, which result in the sunward flowing strahls, while some cases have a signature of interplanetary coronal mass ejections (ICMEs). Multipspacecraft observations by Foullon et al. [2009] confirmed their results.

Obviously, CIRs would have an influence on the leading sector boundaries. In most CIRs, forward shocks or pressure waves could catch up with sector boundaries [Borrini et al., 1981; Thomas and Smith, 1981; Crooker et al., 1999]. Besides, the angular separation between SI and the leading sector boundary decreases significantly as the heliocentric distance increases [Schwenn, 1990]. Although sector boundaries should always lead the SIs [Gosling et al., 1978; Bame et al., 1993; Crooker et al., 1999], observations by the Pioneer and IMP spacecraft showed that SI coincided to within 1 or 2 h with HCS [e.g., Siscoe and Intriligator, 1993, 1994]. However, HCSs and SIs usually have a scale of 10⁴ km [Winterhalter et al., 1994; Forsyth and Marsch, 1999], with a crossing time of only about 1 min, so the time resolution of 1 h is too low to reveal their relative location. More recent conceptual studies suggest that interchange reconnection may be responsible for such coincidence [Crooker and Owens, 2012], but the suprathermal electron data are required to reveal the magnetic configuration related to this coincidence.

In this paper, we report an observation of HCS and SI coincidence using high time resolution in situ data from STEREO A, which is rarely reported for such a short heliocentric distance. We also present the observations of spacecraft nearby including Wind and STEREO B. A schematic model is proposed that could explain the coincidence. The instrument and data are described in section 2. In section 3, we present the multipspacecraft observations. Section 4 presents the discussion, and the main results are summarized in section 5.

2. Data

The twin STEREO spacecraft were launched on 26 December 2006. After a few lunar swing-bys, both spacecraft orbit around the sun at a radial distance of approximately 1 AU, with STEREO A leading ahead and STEREO B trailing behind the Earth. The longitudinal distance between STEREO A and STEREO B increases at approximately 44° to 45° per year when viewing from the Sun (Kaiser et al., 2008). The event we will present occurred on 8 April 2007 when the longitudinal distance between STEREO A and STEREO B was about 3.7°. The observations by the Wind spacecraft are also presented because it was located near L1, right in between STEREO A and STEREO B. Their positions in GSE coordinates on 8 April 2007 are presented in Figure 1 (courtesy of SSCWeb). The STEREO data used in this study are from the In-Situ Measurements of Particles and CME Transients (IMPACT) suite [Luhmann et al., 2008] and the Plasma and Suprathermal Ion Composition (PLASTIC) experiment [Galvin et al., 2008]. The Magnetic Field Experiment [Acuña et al., 2008] of IMPACT provides magnetic field data with a 1 min time resolution, and the Solar Wind Electron Analyzer [Sauvaud et al., 2008] provides the suprathermal electron pitch angle distributions (PADs) with 30 s time resolution. The plasma data provided by the PLASTIC experiment also have 1 min time resolution. The data of Wind used here consist of the plasma and electron pitch angle data from the Solar Wind Experiment [Ogilvie et al., 1995] and the magnetic field data from the Magnetic Field Investigation [Lepping et al., 1995]. They have a much higher time resolution of 3 s.

3. Observations

During the days ahead and following April 2007, the solar activity was quiet in the extended solar minimum of solar cycle 23 [Russell et al., 2010]. There was no ICME documented around this time; therefore, it was ideal
to study undisturbed solar wind. Figure 2 shows the in situ observations by STEREO A, including (from top to bottom) magnetic field RTN components, suprathermal electron PADs, the magnetic field azimuthal angle $\phi_B$, proton specific entropy $S = T_p/n_p^{2/3}$ [Borovsky, 2008], proton number density, bulk speed, and proton temperature. The solid vertical line marks the sharp change of proton density and proton temperature at 21:00 UT. The proton density decreased from a peak value near $60 \text{ cm}^{-3}$ to ~$15 \text{ cm}^{-3}$ and stayed low from then on. The proton temperature increased from $2 \times 10^4 \text{ K}$ to over $10^5 \text{ K}$. The solar wind speed increases slowly from 300 km/s to 528 km/s at 11:00 UT the next day. All of these signatures fit well to the criteria of SI. This stream interface was also documented by Lavraud et al. [2010] and Jian et al. [2013]. Although $\phi_B$ shows some fluctuations during the day, the jump from $-120^\circ$ to more than $225^\circ$ is obvious at 21:00 UT. Before the jump, the phi angle fluctuates around $120^\circ$; after the jump, the phi angle stays at nearly $300^\circ$ with some small variations. The characteristics of the magnetic field suggest an ideal heliospheric current sheet passing exactly the same time as the SI, which is rarely reported at 1 AU.

The dashed line in Figure 2 marks the TSB, when the PADs of suprathermal electrons in the second panel flipped from predominately $180^\circ$ to $0^\circ$. The TSB preceded the HCS by about 6 h, revealing a typical mismatch case. During this interval, the magnetic field lines are directed to the Sun, and the suprathermal electron strahls concentrated on pitch angle $0^\circ$, which means they apparently flow toward the Sun. However, the suprathermal electrons always stream antisunward [Crooker et al., 2004; Lavraud et al., 2010]. Previous studies showed that the interchange reconnection may roll back the magnetic field lines and in turn lead to sunward flowing strahls [Crooker et al., 1996, 2004; Foullon et al., 2009]. We also note that the TSB coincides with a pressure wave characterized by a small increase in magnetic field magnitude and solar wind speed, while the proton density shows a very slight drop.

The separation of TSB and HCS suggests that the IMF may be folded back as a result of some solar wind disturbances. However, the curved magnetic field lines would not explain the coincidence of SI and HCS. For a better understanding of the structure of magnetic field and plasma in the solar wind, we present the observations of STEREO B and Wind below.

Figure 3 shows the observations of STEREO B on 9 April 2007. The plot is nearly in the same format as Figure 2 except for normalized PADs added in Figure 3 (third panel). The normalization is derived by dividing the phase space density in each pitch angle by the mean value of all pitch angles during the same time period. The original PADs of 246.6 eV electrons are also shown in Figure 3 (second panel). Normalization does not modify the physical characteristic of the data but improves the clarity of the plot. The solid vertical line marks the SI crossing at 10:15 UT characterized by the decreased proton density, the elevated proton temperature, and speed. The crossing was more than 13 h later than that observed by STEREO A. However, the expected time difference should be about 2.3 h based on solar wind speed and separation of the two STEREO spacecraft with the data presented in Figure 1 [Opitz et al., 2009; Liu et al., 2014]. The large deviation between observational and theoretical time differences indicates that this boundary may have changed at the origin.
when the solar wind flows out of the sun, which implies that some of the magnetic field configuration may be modified. We note that this SI crossing is also documented by Simunac et al. [2009] and Lavraud et al. [2010].

The HCS cannot be determined on STEREO B since the observed magnetic azimuthal angle fluctuated back and forth from smaller to larger values than 225° a few times starting at 02:00 UT. Therefore, STEREO B did not observe a coincidence of HCS and SI. The magnetic fluctuations may be caused by the planar structure observed from 06:30 UT to 08:40 UT as shown by the shaded region in Figure 3. The angle between the normal of its front and rear boundary is about 8° based on the minimum variance analysis of the magnetic field (MVAB). This planar structure is also characterized by the elevated entropy, smoothly varying magnetic phi angle, enhanced magnetic magnitude, and enhanced strahl flux. Entropy is often used to distinguish different plasmas since it stays unchanged during compression or other adiabatic processes [Pagel et al., 2004; Borovsky, 2008]. The density within the planar structure was significantly smaller and so was the bulk speed. Most of these features are consistent with small flux ropes [e.g., Janvier et al., 2014]; however, the rotation of magnetic field is not observed in the planar structure. This planar structure may not be strong enough to modify the structure of the solar wind; it may result from a reconfiguration of the magnetic field in the solar corona.
The dashed vertical line in Figure 3 marks the TSB crossing near 02:00 UT, which was 11 h later than that observed by STEREO A, and the PADs varied several times after the crossing. This time difference of TSB crossing is approximately equal to the time difference of the SI crossing. In addition, a typical forward shock was observed, when proton density, magnetic field strength, temperature, and solar wind speed all had a steep increase.

The Wind spacecraft observed similar structures like STEREO B as shown in Figure 4. The SI arrived at 05:56 UT on 9 April, 4 h preceding that observed by STEREO B. Based on the solar wind speed and the separation of the spacecraft, the expected time difference is 3.2 h. Similarly, the TSB arrived at 22:40 UT on 8 April as shown by the black dashed vertical line, 3.3 h preceding the TSB observed by STEREO B. Therefore, we concluded that Wind and STEREO B observed the solar wind of the same origin but different from that observed by STEREO A.

The planar structure is also observed by Wind from 01:00 UT to 04:00 UT on 9 April as shown by the shaded region. The characteristics of the planar structure observed by STEREO B and Wind are similar. The angle between the normal of its front and rear boundary is about 17° based on the MVAB. In addition, the proton...
temperature was higher and the suprathermal electron flux was significantly larger compared to adjacent solar wind. Unlike the leading edge of the CIR that overtook the TSB as observed by the twin STEREO spacecraft, Wind found a small forward shock preceding the TSB by 50 min as shown by the blue dashed vertical line, which indicates that the forward shock intruded deeply into the leading slow solar wind.

The multispacecraft observations reveal some important facts. First, the coincidence of SI and HCS and the separation of TSB and HCS are observed on STEREO A. Second, Wind and STEREO B, separated in longitude by only ~350 Rs, observe a much fluctuating magnetic field, and it is therefore not possible to determine the HCS and its relative location with SI. Third, a planar structure which may help to form the fluctuating magnetic fields is observed by both Wind and STEREO B.

4. Discussion

To investigate the coincidence of SI and HCS observed by STEREO A, the trajectories of the spacecraft are projected on the Global Oscillation Network Group’s (GONG) synoptic map along with STEREO B and Wind as shown by the red, blue, and green lines Figure 5a (courtesy of GONG). Due to their very small latitude separations during this time period, the projected lines are nearly overlapping. The red vertical line denotes...
the HCS crossing time at 04:24 UT on 4 April, which is estimated based on the travel time of the solar wind with speed of about 370 km/s. This time fits well with the crossing of the projected spacecraft trajectory (horizontal red line) and the HCS (solid black curve) on the map. Figure 5b shows the synoptic map observed by STEREO A with SECCHI/COR1 at 2.2 solar radii; the brightness denotes the solar wind density. Usually, brighter parts correspond to slow solar wind [e.g., Wang et al., 2000; Sheeley et al., 2009]. After the crossing of the HCS (marked by the red vertical line), the slow solar wind was split into two parts as the red arrows show.

Figures 5c and 5d show the simulated solar wind speed and derived coronal holes (WSA model) using the magnetograms from the Mount Wilcox Observatory as an input (download from CCMC STEREO Support, http://ccmc.gsfc.nasa.gov/stereo_support.php). The red ovals in both panels mark the HCS crossing region. The solar wind speed agrees well with the in situ data. The dark blue band denotes the slow solar wind, which traces the path of HCS, and is also split to a double band as the red arrows show near 5 April just after the HCS crossing. Both the observation and the simulation show that the slow wind split into two parts. The split is usually a sign of a pseudostreamer structure flowing out from the sun, since they are originating from separated coronal holes of the same polarity [e.g., Wang et al., 2007; Simunac et al., 2012; Crooker et al., 2012].

Two nearby coronal holes with the same polarity are necessary for the formation of a pseudostreamer. The derived coronal holes shown in Figure 5d, with the solid black lines connecting the outer coronal boundary and its source regions at the photosphere, are possible explanations for the formation of this pseudostreamer [e.g., Neugebauer et al., 2004; Wang et al., 2012]. Before 5 April, the solar wind mapped to the large positive polar hole (the sign obtained from Figure 5a) in the Southern Hemisphere. After 5 April, the source seemed to be the positive coronal hole located between Carrington longitude 264° and 294° in the same hemisphere at midlatitudes. Two nearby coronal holes exist during this time period; therefore, twin loops can be formed at the boundary of these coronal holes, leading the flow of pseudostreamer [Neugebauer et al., 2004; Wang et al., 2012].

Although the existence of a pseudostreamer is suggested by the observations and the WSA coronal hole predictions, how the pseudostreamer can explain the coincidence of SI and HCS is still not clear. Crooker and Owens [2012] suggested a schematic evolution of the solar magnetic field to explain such coincidence; however, their theory cannot explain the separation of HCS and TSB in our observation.

Interchange reconnection between closed loops from the streamer belt and open magnetic field lines with opposite polarity leads to the separation of HCS and TSB [Crooker et al., 2004]. Owens et al. [2013] pointed...
out that the closed magnetic loops of pseudostreamers could be dragged out by the solar wind, reconnect with open fields at high altitude, resulting in the inverted heliospheric magnetic field. More recent simulations studied the interchange reconnection around the coronal hole boundaries [Edmondson et al., 2009, 2010]. They constructed a small scale bipolar or pseudostreamer-like structure and a global dipole that formed the streamer belt. They showed that the interchange reconnection could happen continuously between the pseudostreamer-like field and the open flux of coronal holes to exchange materials restrained by the closed field.

Our observations suggest that a pseudostreamer formed near the Sun as we observed the coincidence of SI and HCS and the relative separation of TSB at 1 AU. A schematic process is illustrated in Figure 6. The black lines are the magnetic field lines along which the suprathermal electrons flow out. Figure 6a shows the initial state, when the HCS coincides with TSB and both precede the SI. A pseudostreamer appears adjacent to the helmet streamer. At this time, the SI is formed to separate streamer belt flow rather than coronal hole flow. On average, pseudostreamer flow is slightly faster than streamer belt flow [e.g., Wang et al., 2012]. Figure 6b shows the solar wind dragging out the rising loops to meet the open-field lines at higher altitude. The trailing compression on the side of fast solar wind is a magnetic field configuration favorable for interchange reconnection as marked by a yellow circle. Figure 6c pictures the primary topology of magnetic field lines after reconnection. The inverted magnetic field lines marked by yellow color appear, and the open flux between helmet streamer and pseudostreamer reduces. In Figure 6c, the magnetic field lines start to roll back; the suprathermal electrons flow sunward as the red arrow indicates, but the current sheets around the region are local and the HCS still coincides with the TSB.

Figure 6. Schematic of the evolution of the magnetic field configuration in the ecliptic plane. (a) The initial state, a pseudostreamer follows the streamer belt. The HCS coincides with the TSB, and they still lead the SI. (b) Interchange reconnection processes between closed loops from the pseudostreamer and the leading open magnetic field lines. (c) Magnetic field configuration after interchange reconnection, the inverted magnetic field lines appear. (d) Final state, the interchange reconnection reduced the open flux, and the inverted magnetic field lines are dragged to higher altitudes where they can be observed. Consequently, the HCS is shifted to coincide with SI and separates from TSB.

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In Figure 6d, the continuous reconnection process reduces all the open flux in between the original TSB and SI, and the inverted magnetic field lines move to higher altitude. Then, the new SI is developed between the leading slow solar wind and the trailing fast solar wind originating from coronal holes. The slight drops in speed after the crossing of SI as observed by STEREO A and Wind are associated with the interchange reconnection processes [Gosling and Skoug, 2002, and references therein]. It is unlikely that all of the field lines involved in the interchange reconnection would lie in the same plane in three dimensions. To explain the case under consideration, it is reasonable to assume that the rollback field lines (as shown by the yellow line) lie inside the plane of the figure, but the reconnected field lines (dotted portions) lie outside. Consequently, the spacecraft flying in the plane happened to observe the HCS and the SI in the same location, and TSB separated from the HCS.

In addition, the interchange reconnection process could not only result in a rollback of the magnetic field lines but also spreads the slow solar wind to a wider space after reducing the sandwiched open flux. The reduced open flux between TSB and SI may provide a chance for the forward shock to penetrate into slow solar wind deeply as the Wind observation shows.

Neither STEREO B nor Wind observed the coincidence of HCS and SI. Instead, they both observed a planar structure. In addition, the observed time differences suggested that the observed SI originated from the same region but different from what STEREO A observed. It is very likely that the configuration in Figure 6d is evolving, and it is likely to reconfigure, resulting in an SI that originates from a different location as observed by STERO B and Wind. The planar structure may be resulting from the reconfiguration. Further analysis on the origin and the transport of the planar structure will be conducted in our future work. Furthermore, we would like to discuss the source of the streamers on either side of the SI as observed by STEREO B and Wind. Based on the proton and alpha particle (not shown) characteristics, the streamers after the SI should be fast solar wind that originates from coronal holes. However, the situation is more complicated for the source of the solar wind before the SI, when the SI is different from that observed by STEREO A. The source may be similar to that of STEREO A, and the difference could be caused by the evolving interchange reconnection processes. However, the actual source is difficult to pin down.

5. Summary

We first present an event in which the HCS coincides with the SI observed by STEREO A at a distance near 1 AU, with time resolution of 1 min. It is also found that the HCS mismatches the TSB in this event. The origin of such coincidence is explained by pseudostreamer and interchange reconnection near the Sun. Interchange reconnection between the magnetic loops of pseudostreamers and neighboring open fields can lead to the coincidence of the HCS and SI, as schematically shown by the evolution of the magnetic field configuration (Figure 6). Further analysis on STEREO B and Wind data found that they do not observe such coincidence but a planar structure. Thus, we draw the following conclusions:

1. Interchange reconnection between the magnetic loops of pseudostreamers and neighboring open fields can lead to the coincidence of the HCS and SI.

2. A planar structure was observed in the vicinity, and it may be related to the evolving interchange reconnection processes.

3. The pseudostreamer originating from the sun may evolve through reconnection and eventually have the heliospheric current sheet in the vicinity.

References


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