The Astrophysical Journal Letters, 800:L25 (5pp), 2015 February 20 doi:10.1088/2041-8205/800/2/L25

OBSERVATIONS OF A SOLAR WIND DOMAIN BOUNDARY EXTENDING 1 AU FROM THE SUN

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Received 2014 November 14; accepted 2015 January 27; published 2015 February 18

ABSTRACT

We present measurements of a spatially coherent structure that extended over 0.5 AU through the solar wind. This is the first observation of such a feature in white light, and it is rare, possibly unique. While we cannot present conclusive evidence of its origin and nature, we speculate, based on white-light observation and measurement, that it is a domain boundary between fast and slow solar wind streams, possibly arising from the flank of a coronal mass ejection that erupted some 10 hr prior to its appearance. The puzzling aspect of this feature is that it maintained its structural integrity for several days in the solar wind at distances near 1 AU, yet it showed no signs of turbulent break up. This is despite an expectation, which we derive from basic hydrodynamic theory, that turbulence induced by the Kelvin–Helmholtz instability should at least be present there. We present our observations, measurements, and speculations and conclude with an appeal to the wider community for suggestions as to the source, nature, and uniqueness of this feature.

Key words: instabilities – solar wind – Sun: corona – turbulence

Supporting material: animation

1. INTRODUCTION

The nature of the solar wind in the inner heliosphere remains a topic of much debate and exploration. While it is broadly accepted that the solar wind possesses properties that are theoretically expected in a magnetohydrodynamic medium, we have, until recently, been limited to single-track in situ observations to confirm the presence of these properties. For example, the influence of solar wind turbulence on the transient features embedded in the solar wind remains an ongoing puzzle (see Petrosyan et al. 2010 for a recent review). Many transient features, such as coronal mass ejections (CMEs), polar plumes, and streamer cusps, maintain their morphological integrity at large distances from the Sun (e.g., Cranmer et al. 2013 and references therein).

It is well known that the solar wind consists of distinct domains of fast and slow speeds, the former associated with fields that are not bipolar and have a low density, while the latter are generally bipolar and have a high density (e.g., McComas et al. 1998a; von Steiger et al. 2000). The physics of the boundary between these domains remains a topic of some debate. The Kelvin–Helmholtz instability (KHI) occurs as a result of two dynamic fluids of different speeds and densities in contact with each other. At the interface between the two fluids, a velocity shear is present and can develop into turbulent flow (see, e.g., Chandrasekhar 1961). In most fluid dynamic systems, the KHI develops at interfaces between streams of different speeds and densities, breaking up hard boundaries even in inviscid flow. Yet strong and sharp shears can develop and persist at domain boundaries, such as corotating interaction regions, and they persist even at large distances from the Sun (Pizzo 1978, 1980, 1982).

Heliospheric imaging (Eyles et al. 2003, 2009) has enabled, for the first time, a global view of the influence of the solar wind on embedded transient structures, including the presence of turbulence. We are no longer restricted to awaiting the impact of features of interest with in situ spacecraft to investigate the influence of the solar wind upon them; instead, we have high-cadence wide-field imagery of density structures in the solar wind extending 90° of elongation from the Sun. This enables the study of smaller features that would typically have a very low probability of impacting a single point in the ecliptic plane and the direct comparison with coronagraph and solar observations (see Howard et al. 2012 for a recent study).

We present measurements of a remarkable feature observed in visible white light by the SECCHI instrument suite on the *STEREO-A* spacecraft: a straight line extending at least 1.2 AU (70° in angle) from the Sun. Despite the sharpness of the feature, it does not exhibit visible dissipation, break up, or distortion as would be expected in a turbulent flow. The feature persisted for at least five days after its origin in the wake of a CME. While we can only provide rudimentary measurements of the feature from the white-light observations alone, since the feature did not impact any spacecraft and we found no evidence of its departure in solar disk imagery, we interpret it to be a sharp boundary between fast and slow solar wind domains. Following a first-order hydrodynamic (HD) analysis of the theory of KHI, we find that it would be reasonable to expect the presence of KHI turbulence at detectable scale sizes here, suggesting that this feature is either resistant to the effects of such turbulence or that the turbulence is either smaller than expected here or not present. We are open to suggestions by the wider community as to the possible nature of this mysterious structure.

2. DESCRIPTION OF THE DOMAIN BOUNDARY

The feature is visible in white-light images of Thomson scattered light, collected by the *STEREO-A* spacecraft from 2011 April 4 to 9. We have not observed such a feature over any other timeframe and have not found any reports of such a structure in the literature. It is therefore rare, possibly unique, in the solar wind. The feature did not pass over any in situ probes, and while we inspected imagery of the solar disk (EUV and magnetogram), we did not find evidence of a solar "surface" manifestation of the feature. From a solar disk perspective, we note that a large portion of the northwestern quadrant of the Sun (relative to the Earth) was magnetically active and that the associated CME that erupted a few hours prior to the feature's appearance in white light (see Section 2.1) was associated with a post-eruptive arcade (Tripathi et al. 2004). We did not, however, identify any noteworthy eruption or field reconfiguration in the solar disk imagery around the time of the departure of our feature of interest. Our primary measurements are therefore morphology and density, both inferred from the apparent brightness of the feature. These limited observations enable us to only speculate as to the nature and origin of the feature, but we regard this as satisfactory given that such a feature has not been reported upon in prior literature.

2.1. Coronagraph Observations

The feature appears to follow in the wake of a CME that was launched on 2011 April 4, probably along its northern flank. Figure 1(a) shows COR2-A and COR2-B images from 15:24UT on that day. *SOHO*/LASCO data were not available for the duration of this CME, but given the location of the *STEREO* spacecraft at this time (both approximately at quadrature with the Sun–Earth vector), the direction of the CME relative to both spacecraft, and the arrival of what appears to be an interplanetary shock in the in situ data from *ACE* and *Wind* at around 09:00 UT on April 6, we conclude that the CME was Earth directed. Figure 1(b) shows the CME and indicates a radial "spoke" that remained intact after the CME had left the Sun. While the COR2-B image shows the spoke as embedded within the wake of the earlier CME, the COR2-A image shows it to be separated from the base of the main body of the CME, shown here as the bright feature below the spoke. The spoke appears to be related to another structure that launches with, but is not necessarily a component of, the prior CME. This spoke extends out through the fields of view of the COR and HI instruments, ultimately forming a visible straight line structure extending to 70° from the Sun in the HI-2A field of view.

Later in the day, around 14:00 UT, our feature of interest appears in the COR2 fields of view. Figure 1(c) shows it at 15:24 UT when it was around 7 $R_{\odot}$ from the Sun. It appears to be aligned along the northern flank of the prior CME. The separate structure to its south, which appears to contain a small cavity, launches ahead of and with a higher speed than a fainter eruption to its north, yet it is this fainter structure that is the feature of interest for our paper. Note that immediately north of the feature is a region that is less bright than the region to the south (most easily identified in the COR2-B image). These observations lead us to speculate that the feature lies along the interface between two solar wind domains, possibly created by the passage of the prior CME.

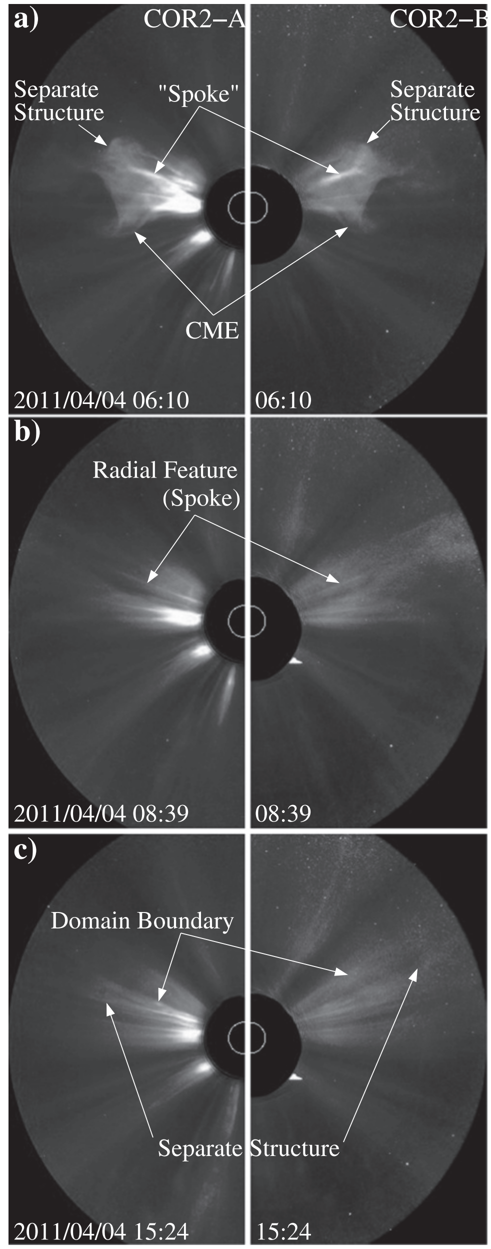

Figure 1. (a) *STEREO* COR2-A (left) and COR2-B (right) images of the CME that our feature followed; both images were obtained at 06:10 UT on 2011 April 4. Indicated by arrows and labeled are features of interest. (b) COR2 images a couple of hours later at 08:39 UT, with the remnant radial feature along which our feature appears to be guided highlighted by the arrows. We also indicate the location of the base of the prior CME in each image. (c) COR2 images of the feature itself during its launch; these images were obtained at 15:24 UT.

2.2. Heliospheric Imager Observations

Figure 2 shows a sequence of still frames from the movie that is included with this Letter. We see the evolution of the feature continuously from the fields of view of COR2-A, through HI-1A and then HI-2A. Figure 3 shows a frame from the HI-2A movie (note that the movie frames are rotated 90° from the figure, the latter presented in this way for direct comparison with Figure 2). We see the feature moving slowly across the field of view of HI-2A, but its structure is maintained until at least the end of April 9. We also note a small lateral movement (i.e., movement in the negative x (y) direction in Figure 3 (the movie frames)) throughout the movie. There is insufficient information to draw conclusions about the nature of this apparent lateral motion, but we speculate that this is the geometrical manifestation of corotation of the feature. It is known from studies of corotating interaction regions with heliospheric imagers that time-stationary corotating structures exhibit lateral motion in the HI-2A field of view (e.g., Rouillard et al. 2009; Tappin & Howard 2009).

2.3. Location in Three Dimensions

We estimated the feature's location in three-dimensional (3D) space using geometric triangulation from the *STEREO-A* and *STEREO-B* viewpoints, with the method of Howard & Tappin (2008). We found the direction of propagation of the feature at around 28°N48°W, i.e., north of the ecliptic and between the Earth and *STEREO-A*.

With a 3D location, we can estimate some structural and kinematic properties of the feature. To estimate its distance, we measured the leading edge of the feature in all three imagers (COR2-A, HI-1A, and HI-2A). We compared two separate approximations: Point-P, where the measured points are assumed to lie on the Thomson surface (e.g., Howard et al. 2006), and Fixed-Φ, where the measured point is assumed to be exactly a point in 3D space (e.g., Howard et al. 2007). We rely on the Fixed-Φ estimations for the speeds presented in this Letter, as the feature is sufficiently "point-like" in the azimuthal sense and Point-P is known to be unreliable at large elongations (e.g., Howard & Simnett 2008). Finally, we apply the first-order assumption that the 3D location of the feature is fixed, i.e., that its movement in the white-light imager field of view is strictly due to radial propagation, thereby disregarding the corotation mentioned in Section 2.2 as small relative to the radial speed. Figure 4 shows the (radial) distance–time plot of the feature, with the radial distance R converted from elongation units using Fixed-Φ. We obtained the following estimates for the speeds in each of the fields of view: COR2 = 425, HI-1 = 435, and HI-2 = 380 km s^{-1}.

The image sequence shown in Figure 2 provides background-subtracted measurements of features calibrated to units of solar brightness. This enables us to determine the mass of our feature of interest and, assuming a particular volume, an electron density ρ_s. Keeping with our simple analysis, we assumed that the volume was a cylinder of 0.5 AU length and a cross-sectional diameter of 0.17 AU (10°) and made five measurements of the feature brightness (radiance) across its span in HI-2A. We arrived at a mean density ($\pm\sigma$) of 8.3 ± 1.2 cm^{-3}. This density, along with our estimated speed of 380 km s^{-1} in HI-2A, agree broadly with in situ measurements of density and speed of the slow solar wind near 1 AU (e.g., McComas et al. 1998b and references therein).

3. SHOULD WE EXPECT THE PRESENCE OF KHI?

We begin with the assumption that the domain boundary is between typical fast and slow solar wind domains; the latter is, to some extent, verified by our measurements of the density and speed of the bright portion of the boundary (Section 2.3). Given that our measured feature is a boundary between domains of different speeds and densities, one might expect the KHI to be present, possibly to the extent that it is visible within features of the scale size of our feature of interest. In such scenarios, the KHI growth rate refers to the complex solution to the wave perturbation equation that is exponentially growing (e.g., Chandrasekhar 1961). For the purposes of this investigation, we focus on the HD solution of KHI. While we acknowledge that the full MHD treatment will likely yield results different to those presented here (KHI suppression due to the presence of a magnetic field has been suggested), our analysis is suitable given the limited scope of this Letter and the first-order approach we have adopted for this first-time observation.

In subsonic regimes, neglecting surface tension and gravity, the growth rate $n_{\rm KH}$ is

$$n_{\rm KH} = \frac{k_m}{\rho_f + \rho_s}\sqrt{\rho_f \rho_s \Delta V^2}, \qquad (1)$$

where f and s refer to the fast and slow solar wind domains, respectively; ρ is the electron density; $\Delta V = V_f - V_s$ is the difference in speed between the two domains; and k_m is the wavenumber of the KHI disturbance. Higher k_m yields faster growth. The smallest radial feature we can observe in HI-2A data is about 3° in apparent size, limited by motion blur. This feature size, corresponding to about 6 mAU, or $k_m \sim 7 \times 10^{-6}$ km^{-1}, is therefore the fastest-growing mode in the observable range. We use the speed and density values determined from our measurements of the bright feature for the slow domain (Section 2.3): $V_s = 380$ km s^{-1} and $\rho_s = 8.3 \pm 1.2$ cm^{-3}. As we are unable to measure the fast solar wind in this scenario, we select typical values of the fast solar wind speed and density: $V_f = 600$ km s^{-1} and $\rho_f = 5$ cm^{-3}. This yields a growth rate of $(7.4 \pm 0.1) \times 10^{-4}$ s^{-1}, meaning that it would take 22 minutes for the HD KHI disturbance to reach the HI-2 spatial resolution limit. With this growth rate, we would expect the KHI to disturbance to have reached an amplitude of around 20° by the time the domain boundary reached the HI-2 field of view. Even accommodating for the magnetic field suppression, we should reasonably expect the feature to have been notably affected, if not completely dispersed by KHI turbulence.

4. DISCUSSION

We have identified what we speculate is a solar wind domain boundary that was present at around 1 AU from the Sun and extended, as a smooth straight line, a distance of at least 0.5 AU. To our knowledge, this is the first time such a boundary has been observed directly. Our results show that if the KHI were present, it would probably have produced a visible signature on the feature in the HI-2 field of view. We found no such signature affecting the structure of our feature.

There are three possible explanations for the absence of observable turbulence on the domain boundary: that the feature possesses some intrinsic property that impedes turbulent forces, that there is a significant property of turbulent theory that we have not considered here, or that turbulence was not present in the solar wind. The first possibility is likely the case with large-scale structures such as CMEs and CIRs, which are known to contain intrinsic field structures that almost certainly maintain their structural integrity. We must consider the possibility that the domain itself may possess intrinsic magnetic properties that serve as a barrier to turbulence. The second possibility includes the influence of non-KHI turbulence or that physical properties such as the magnetic field may depress the effects of KHI so substantially as to render it undetectable in the HI-2 field of view. A full exploration requires an extensive theoretical investigation of the MHD theory of turbulence that is well beyond the scope of the present Letter.

The third possibility is consistent with the findings from the modeled results of Odstrčil (1994), Pizzo (1994), and Odstrcil & Pizzo (1997). Additionally, we note a feature highlighted by Odstrčil (1994, his Figures 3 and 5) and termed a "cocoon," which is formed by the rapid deceleration of the fast domain

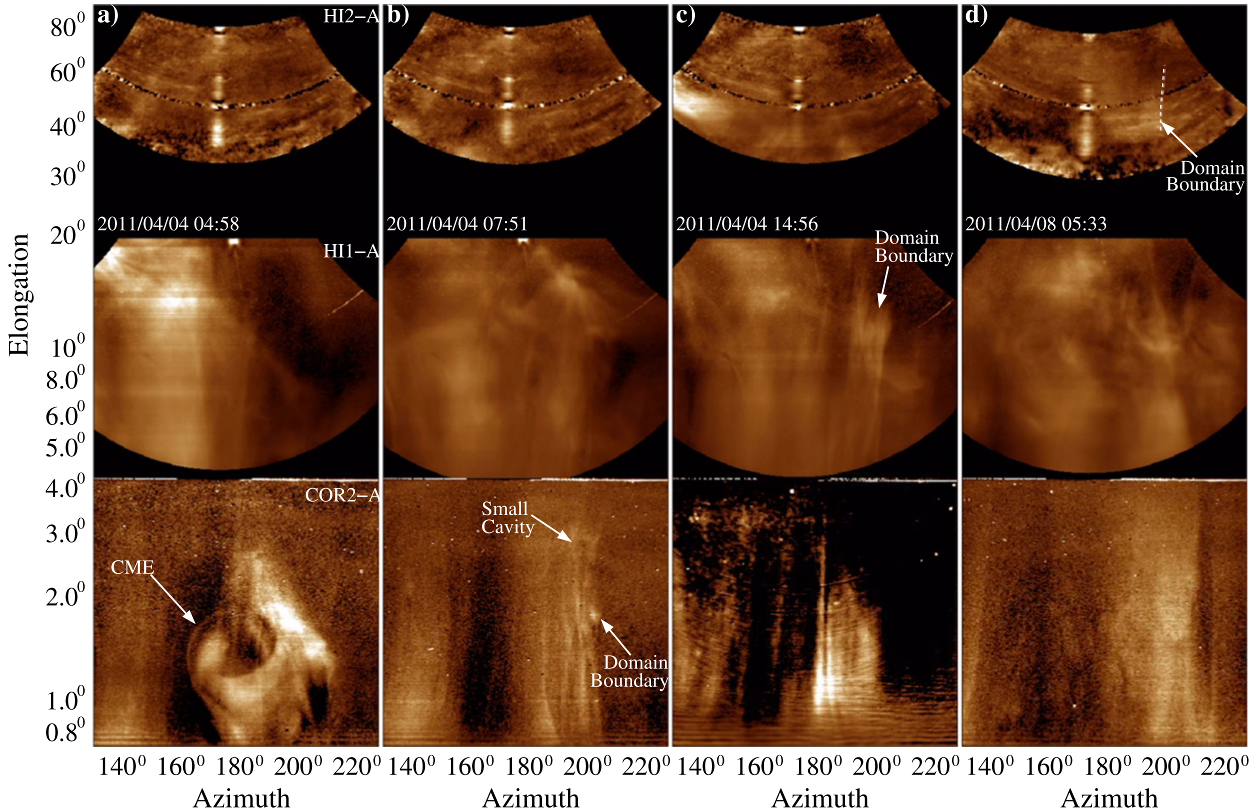

Figure 2. Sequence of still frames from the included movie, showing the SECCHI (COR2-A, HI-1A, and HI-2A) combination of images for the feature of interest. The images have been passed through our SECCHI processing pipeline (DeForest et al. 2011; Howard & DeForest 2012; Howard et al. 2012) and have been scaled by azimuth and elongation, with a log scale for the latter. The sequence of frames is as follows: (a) image of the CME at 04:58 UT for comparison with Figure 1(a); (b) image of the launch of the feature of interest at 07:51 UT, again for comparison with Figure 1(c); (c) the feature of interest as in HI-1A as a solar wind "puff" with an apparently rigid straight line trailing its northern flank; and (d) the feature in HI-2 at 05:33UT on April 8, when it was 60° from the Sun and spanned a distance of more than 20° of elongation.

(An animation of this figure is available.)

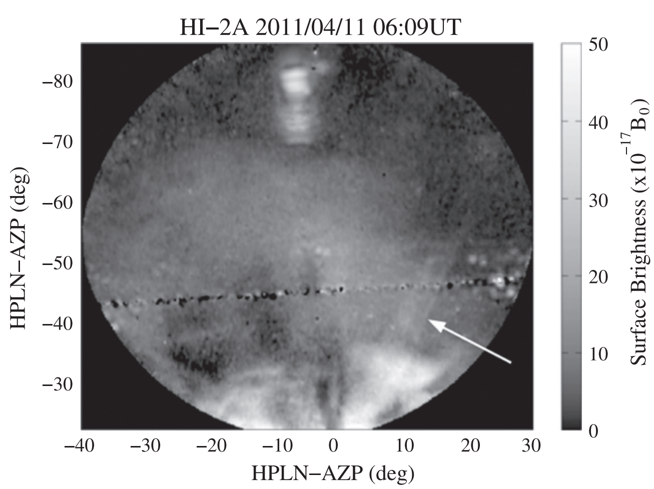

Figure 3. HI-2A image from 2011 April 8, 06:09 UT, showing the structure of the domain boundary with the white arrow. As with Figure 2, these have been processed through the processing pipeline (DeForest et al. 2011).

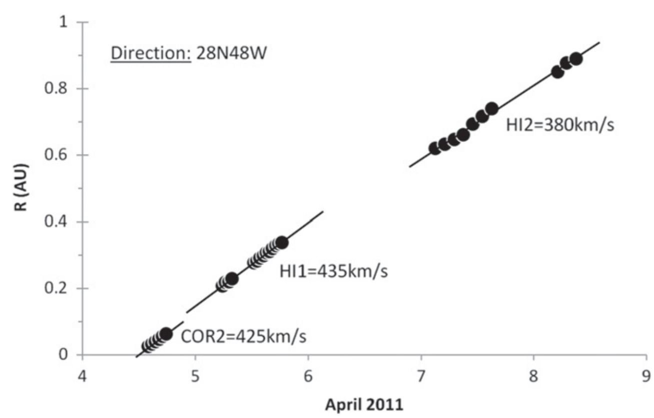

Figure 4. Distance–time plot of the domain boundary using measurements of its leading edge from COR2, HI-1, and HI-2. Distance was converted from units of elongation using the Fixed-Φ approximation, assuming the feature was traveling at a direction of 28°N48°W from the Sun–Earth line. The speeds from each observatory determined from their distance–time plot are labeled.

through a reverse shock, causing an accumulation of compressed plasma behind the contact discontinuity. The dimensions of this cocoon, around 0.2 AU at distances of around 1 AU, agree remarkably well with the dimensions of our domain boundary measured in HI-2. KHI theory describes the instability occurring only when particular boundary conditions are met. When the velocity shear is sufficiently large, the interaction occurs in a so-called supercritical state, and the KHI theory no longer applies. It has been suggested (Odstrcil & Pizzo 1997) that the system enters a supercritical state when the boundary is between two supersonic domains, such as in both the slow and fast solar wind domains.

We stress that there is insufficient evidence to conclude any of the three possibilities discussed above. The purpose of this Letter is to highlight the feature as one of interest and to appeal to the wider community for a possible description as to its nature uniqueness. We have provided the measurements we are able to from the white-light observations and made some speculations about how it might arise, but an accurate description remains outstanding.

More broadly, our Letter expands upon a growing field where heliospheric imaging is utilized to directly measure properties of the solar wind. Such utilization promises to solve many more outstanding controversies in the solar wind literature.

SECCHI data are produced by a consortium of international groups, including NASA, RAL, NRL, UBHAM, MPS, CSL, IOTA, and ITAS. We thank NRL, NASA, and RAL for their maintenance and provision of the *STEREO* data set. Work for this paper was partially funded by the NSF SHINE competition 1260321 and NASA/GI grant NNX13AE01G. We also thank D. Odstrcil and V. Pizzo for invaluable discussions during the development of this work.

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