Morphological Reconstruction of a Small Transient Observed by \textit{Parker Solar Probe} on 2018 November 5

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Abstract

On 2018 November 5, about 24 hr before the first close perihelion passage of \textit{Parker Solar Probe} (PSP), a coronal mass ejection (CME) entered the field of view of the inner detector of the Wide-field Imager for Solar PRoBe (WISPR) instrument on board \textit{PSP}, with the northward component of its trajectory carrying the leading edge of the CME off the top edge of the detector about four hours after its first appearance. We connect this event to a very small jetlike transient observed from 1 au by coronagraphs on both the \textit{SOlar and Heliospheric Observatory} (SOHO) and the A component of the \textit{Solar TErrrestrial Relations Observatory} mission (STEREO-A). This allows us to make the first three-dimensional reconstruction of a CME structure considering both observations made very close to the Sun and images from two observatories at 1 au. The CME may be small and jetlike as viewed from 1 au, but the close-in vantage point of \textit{PSP}/WISPR demonstrates that it is not intrinsically jetlike but instead has a structure consistent with a flux rope morphology. Based on its appearance in the \textit{SOHO} and \textit{STEREO-A} images, the event belongs in the “streamer blob” class of transients, but its kinematic behavior is very unusual, with a more impulsive acceleration than previously studied blobs.

\textit{Unified Astronomy Thesaurus} concepts: Solar coronal mass ejections (310); Solar K coronal region (2042); Solar coronal transients (312)

Supporting material: animations

1. Introduction

Most studies of coronal mass ejections (CMEs) naturally focus on the biggest, fastest, and brightest events, which are also the ones that are the most geoeffective when they happen to hit Earth. However, CMEs come in a wide range of sizes and speeds, with smaller, slower events being more numerous than the large, fast ones (Yashiro et al. 2004; Vourlidas et al. 2017; Wood et al. 2017). Due to their greater frequency, the smaller transients may collectively account for a significant fraction of what is generally regarded as the quiescent slow solar wind (Kilpua et al. 2009; Janvier et al. 2014).

For small transients observed in white-light (WL) images, it can be ambiguous whether “CME” is the best descriptive moniker. For example, using observations from the Large Angle Spectrometric COronagraph (LASCO) instrument on board the \textit{SOlar and Heliospheric Observatory} (SOHO), Sheeley et al. (1997) identified a class of small jetlike transients emanating from the tops of helmet streamers, which could generically be termed “streamer disconnection events,” but have been more informally called “streamer blobs” (Wang et al. 1998). These events have slow acceleration profiles that are believed to simply track the ambient slow solar wind into which they are released (Cho et al. 2018). Likewise, CMEs that have no associated solar surface activity have similarly slow acceleration profiles, and though some of these events can be large and bright, some are as small and faint as the streamer blobs (Wood et al. 2017). The distinction between streamer blobs and the slow CMEs is also blurred by morphological similarity. The stereoscopic imaging capabilities provided by the \textit{Solar TErrrestrial Relations Observatory} (STEREO) mission have provided evidence that streamer blobs have a flux rope (FR) structure (Sheeley et al. 2009; Rouillard et al. 2011), consistent with the most favored interpretation of CME morphology (Chen et al. 1997; Bothmer & Schwenn 1998; Thernisien et al. 2009; Vourlidas et al. 2013; Wood et al. 2017).

Even further along the spectrum from large, obvious transients toward smaller density enhancements within the solar wind are the periodic density structures identified in coronagraphic and heliospheric images (Viall et al. 2010; Viall & Vourlidas 2015). DeForest et al. (2018) find that such compact solar wind structures possess a continuum of sizes, with the streamer blobs at the large-scale end. Some of these structures might be associated with reconnection among streamer loops, while others might be associated with interchange reconnection between closed loops and open flux at coronal hole boundaries, as suggested by recent numerical modeling (Higginson et al. 2017; Higginson & Lynch 2018).

The launch of \textit{Parker Solar Probe} (PSP) on 2018 August 12 provides an opportunity to study small solar wind transients from a vantage point closer to the Sun, allowing a more detailed inspection of their structure. During each close perihelion passage of \textit{PSP}, the plasma instruments can detect such transients in situ, and the Wide-field Imager for Solar PRoBe (WISPR) instrument can provide close-up images of these events. The first close perihelion passage occurred on 2018 November 6, with \textit{PSP} reaching 35.4 R\textsubscript{\textast}} from Sun-center. We here report on a small CME observed by WISPR a day earlier, which is also observed by coronagraphs on both \textit{SOHO} and \textit{STEREO-A}. The resulting stereoscopic imaging allows us, for the first time, to study CME morphology considering both multiple vantage points at 1 au and a viewpoint very close to the Sun.

2. Observations

The first perihelion passage of \textit{PSP} occurred at UT 03:28 on 2018 November 6, at 35.4 R\textsubscript{\textast}} from Sun-center. About 24 hr earlier, the WISPR imager on \textit{PSP} observed the small CME
Figure 1. Positions of Earth, PSP, STEREO-A, and STEREO-B in the ecliptic plane on 2018 November 5 (in HEE coordinates). The blue lines indicate the FOV of the LASCO/C3 coronagraph on SOHO, near Earth. The purple lines indicate the FOV of COR2-A on STEREO-A, and the green and red lines are the FOV’s of WISPR’s Detector 1 and Detector 2, respectively. The dashed line indicates the central trajectory of the small CME observed by LASCO, COR2-A, and WISPR on November 4–5.

that is the subject of this article, which was also detected by SOHO/LASCO and STEREO-A. Understanding these observations requires knowledge of the viewing geometry involved, which is shown in Figure 1. A heliocentric Earth ecliptic (HEE) coordinate system is used, with the x-axis pointed from the Sun toward Earth, and the z-axis pointed from the Sun toward ecliptic north. The SOHO spacecraft is located near Earth, specifically at the L1 Lagrangian point. The LASCO instrument on SOHO includes two coronagraphs, C2 and C3, observing the WL corona at Sun-center distances in the plane-of-sky of 1.5–6 Rs, and 3.7–30 Rs, respectively (Brueckner et al. 1995). The field of view (FOV) of the latter is shown explicitly in Figure 1. Also shown is the FOV of the COR2-A coronagraph on STEREO-A, covering 2.5–15.6 Rs (Howard et al. 2008).

The WISPR instrument on PSP possesses two heliospheric imagers, Detector 1 and Detector 2, which look in the ram direction of PSP’s orbit around the Sun, covering elongation angles from Sun-center of 13°–53° and 50°–108°, respectively (Vourlidas et al. 2016). These FOV’s are also explicitly shown in Figure 1, although the CME in question never actually enters the Detector 2 FOV. Although STEREO-B’s location is indicated, observations from it are unfortunately not available, as STEREO-B has not been operational since late 2014.

Figure 2 shows a sequence of four WISPR Detector 1 images from UT 4:43 to UT 9:56 on 2018 November 5, with a small CME entering on the upper left side of the detector and eventually exiting off the top of the FOV. Generating such WL images requires first removing the dust-scattered F-corona contribution, which is performed as a part of the WISPR data processing, analogous to what has been done for STEREO data (e.g., Stenborg & Howard 2017). This is somewhat more complicated for WISPR than for WL images from 1 au observatories, because PSP’s distance from the Sun is changing significantly during the observations, and, therefore, the F-corona background is time dependent. Removal of this background yields a WL image that includes only the K-corona contribution of interest, which is due to Thomson scattering from electrons. The K-corona images are dominated by emission from the quiescent streamer structure, but we wish to focus on the emission from the transient emission. Thus, we compute an average K-corona image from November 5 and then subtract this from all the images to emphasize the variable emission. We also use median filtering to suppress stellar point sources. The images in Figure 2 have been cropped on the bottom and right sides to focus attention on the location where the CME is observed.

We connect the November 5 CME observed by WISPR with a tiny transient observed by SOHO/LASCO on November 4–5. Figures 3 and 4 show a sequence of LASCO images from this time period. In Figure 3, the images are shown after subtracting a monthly minimum image, which preserves the appearance of the quiescent streamer structure, while in Figure 4, four C2 images are shown in a running-difference format, which makes the small transient easier to see. There are actually two small transients observed by LASCO: one to the south marked by a green arrow in Figure 3 and one to the north marked by a red arrow. The latter corresponds to the CME observed by WISPR. The simultaneity of the two transients suggests that they are related, both possibly resulting from a minor adjustment to the large-scale streamer structure on the west side of the Sun. In terms of their small size and clear association with the streamer structure, both events seem consistent with the “streamer blob” class of transients (Sheeley et al. 1997; Wang et al. 1998), although we will show below that the WISPR-observed event has an impulsive acceleration that is very atypical for streamer blobs. Note that despite their small size, both of these events make it into the online Coordinated Data Analysis Workshops (CDAW) CME catalog (Yashiro et al. 2004; https://cdaw.gsfc.nasa.gov/CME_list), with listed start times of UT 22:12 and UT 22:36 on November 4 for the south and north events, respectively.

The origin of the event of interest is clearest in Figure 4, where the outflow begins in the middle of the FOV. There is evidence for a pinch-off region, like the events described by Sheeley & Wang (2007), leading not only to the outflowing blob but also an apparent downflow below it. This is clarified in the height–time stack plot shown in Figure 4(e), where traces of the running-difference C2 intensities at the position angle of the event are stacked. In this plot, the transient is seen as parallel bright and dark streaks with positive slopes, indicating an outflow. A dark streak below it with a negative slope indicates the apparent downflow.

The small WISPR CME is also observed by COR2-A, as shown in Figure 5. These images are shown after the subtraction of an average COR2-A image from November 5 in order to better reveal the faint transient. The angular extent of the CME in COR2-A is somewhat wider than in the LASCO images in Figures 3–4, where the CME is particularly narrow and jetlike.

It is not surprising that the CME would look much bigger in the WISPR images than in LASCO and COR2-A images from 1 au, considering how much closer PSP is to the event (see Figure 1). However, the most important characteristic to note about the CME’s appearance is that, unlike in the LASCO and
COR2-A images, the CME in WISPR is not jetlike at all. Instead, the transient in WISPR looks very much like an FR structure, with two legs stretching back toward the Sun. Its appearance is dominated by one leg that ultimately stretches through the FOV from east to north, but at early times, it is clear that the CME structure is not linear but bends up and then backward, presumably curving into a second leg that is almost entirely above the FOV. Note that the lower leg remains visible long after the leading edge of the CME has moved out of the FOV, suggesting continued magnetic connectivity with the Sun.

Magnetic FRs can be described as tube-shaped structures permeated by a helical magnetic field, with legs that stretch back toward the Sun (Bothmer & Schwenn 1998). Evidence that FRs are at the core of all CMEs comes from both in situ plasma measurements (Lepping et al. 1990; Richardson & Cane 1996) and WL imaging (Chen et al. 1997; Thernisien et al. 2009; Vourlidas et al. 2013; Wood et al. 2017). Our observations provide further support for this interpretation, demonstrating that small CMEs that look linear and jetlike from 1 au are revealed to have an FR appearance when viewed up close. We now perform a detailed three-dimensional (3D) reconstruction of the CME to demonstrate this more explicitly.

3. Morphological Reconstruction

We reconstruct the 3D structure of the CME assuming an intrinsic FR shape, using techniques that have been developed to interpret CME images from the STEREO spacecraft (Wood & Howard 2009; Wood et al. 2017). We refer the reader to these previous works for details, but in short, the shape of the inner and outer edges of a 2D FR are defined in polar coordinates, and then the two 2D loops are used to define a 3D FR shape by assuming a circular cross section for the FR, bounded by the two loops. By stretching the FR in the direction perpendicular to the FR creation plane, an FR can be created with an arbitrary ellipticity. The 3D FR is then rotated into the desired orientation in an HEE coordinate system. Adjusting the various quantities involved in the FR creation process allows experimentation with different shapes and orientations. For confronting the model FR shape with the actual images of the CME, mass is first placed onto the surface of the 3D FR shape, but not in the interior, and then synthetic images of the resulting density cube are computed, based on calculations of the Thomson scattering within the density cube. The assessment of the best fit relies on subjective judgment, with the best-fit parameters discerned through trial-and-error. The shape of the CME structure is not assumed to vary at all, meaning we assume the structure expands in a self-similar fashion.

Figure 6 shows our morphological reconstruction of the CME, in an HEE coordinate system. The FR is shown at two times, UT 3:48 and UT 9:40, corresponding to the beginning and end of the movie version of Figure 2. The location of PSP at these two times is also indicated. The synthetic images of the CME based on this reconstruction are shown in Figures 2, 3, and 5, for comparison with the real images. The reconstruction successfully reproduces both the CME’s appearance in the WISPR images (Figure 2) and the narrow, jetlike appearance in the LASCO data (Figure 3). The reconstructed FR is almost perfectly edge-on as viewed from SOHO’s perspective, explaining why it is so narrow in the LASCO images.

We consider the synthetic COR2-A images to be an adequate reproduction of the observations (see Figure 5), but deviations from the data are larger here. Specifically, the FR leg that is slightly higher in the COR2-A images is predicted to be brighter than observed. This is the left leg in Figure 6, which is the leg that is mostly out of the WISPR FOV in Figure 2. We suspect that improved agreement with the data could only be
achieved by introducing asymmetries of some sort into our FR structure. Our parameterized FR shape is a symmetric one, with mass placed onto its surface in a symmetric fashion, increasing 

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and, therefore, is a measure of how thin the FR is. The $\Lambda_r = 0.039$ value in Table 1 is indicative of a very thin FR, thinner than any in the Wood et al. (2017) sample. Our FR reconstruction scheme allows for the possibility of an elliptical FR channel, but we see no evidence for ellipticity, so $\eta_e = 1.0$. Finally, the $\alpha_s$ parameter defines the shape of the FR leading edge (see Wood et al. 2017), with higher values leading to flatter leading edges. Our rather low $\alpha_s = 2.5$ value yields a leading edge that is better described as curved rather than flat.

### 4. Kinematics

Computing the synthetic images in Figures 2, 3, and 5 requires not only the morphological reconstruction shown in Figure 6 but also a kinematic model to describe how the structure expands with time. Our kinematic measurements of the CME are based on the LASCO measurements, as LASCO has the best vantage point for tracking the leading edge of the CME. The top panel of Figure 7 shows distance measurements from the C2 and C3 coronagraphs, with measured elongation angles converted to distances, assuming the CME trajectory direction found from the morphological analysis. In order to infer a velocity profile for the CME, we fit a simple two-phase kinematic model to the data, assuming a phase of constant acceleration followed by a phase of constant velocity. In the resulting kinematic fit, the CME accelerates at a rate of 45.3 m s$^{-2}$ for about two hours before leveling out at a final speed of 439 km s$^{-1}$.

Although the final speed of the CME is not particularly fast and is comparable to slow solar wind speeds, the kinematic profile still involves a surprisingly impulsive acceleration. In order to illustrate this, in Figure 8, we compare the CME’s kinematic behavior with that typically observed for streamer blobs and slow CMEs. The streamer blob profile is based on

![Figure 3. Sequence of images from the LASCO C2 and C3 coronagraphs on board SOHO, showing two little transients whose positions are marked by red and green arrows. The upper event corresponds with the CME observed by WISPR. Synthetic images of this transient are shown below the real images, based on the 3D reconstruction described in Section 3. The C2 coronagraph sequence is at the start of the video in the first second of real time. C2 begins at 2018 November 4 22:00:05 and ends the next day at 00:36:05. C3 follows in the last second. It runs from 2018 November 5 00:06:06 and ends at 2018 November 5 06:30:05. (An animation of this figure is available.)](image-url)
Figure 4. (a)–(d) Sequence of four running-difference images from the LASCO C2 coronagraph, focused on the transient observed by WISPR. (e) A height–time stack plot for the position angle of the transient, with arrows pointing toward the outflow and below it in an apparent inflow.

Figure 5. Sequence of two images of the 2018 November 5 CME from the COR2-A coronagraph on board STEREO-A. Synthetic images of this transient are shown below the real images, based on the 3D reconstruction described in Section 3. The video begins on 2018 November 5 01:01:00 and ends the same day at 11:41:00. The real time video duration is 3 s.

Figure 6. Reconstructed 3D FR structure of the CME observed by PSP/WISPR on 2018 November 5, shown in HEE coordinates. The FR is shown at two times, t1 and t2, corresponding to UT 3:48 and UT 9:40, respectively. The red circles indicate the location of PSP at these two times. The size of the Sun is to scale.
velocity versus distance measurements of about 80 events from Wang et al. (2000). We place these measurements into 0.1 $R_e$ distance bins and compute the average velocity within each bin, yielding the blob kinematic profile in Figure 8. For the slow CMEs, we compute the average kinematic profile of the “Group 3” CMEs in the Wood et al. (2017) sample of Earth-directed events, where “Group 3” CMEs are ones with no accompanying surface activity (e.g., flares or filament eruptions). These CMEs overlap the “streamer blowout” category of transients (Howard et al. 1985; Vourlidas & Webb 2018). At this point, we should mention that inspection of images from the Solar Dynamics Observatory reveals no evidence of surface activity associated with the November 5 CME, but its trajectory would suggest a source 17° behind the limb as viewed from Earth, so we cannot be completely certain that no surface activity accompanies the eruption.

Table 1

| Parameter | Description                      | Value |
|-----------|----------------------------------|-------|
| $\alpha$  | Trajectory longitude             | 107   |
| $\beta$   | Trajectory latitude              | 13    |
| $\gamma$  | Tilt angle of FR                 | 5     |
| FWHM      | Angular width                    | 43.6  |
| $\lambda_r$ | Aspect ratio                   | 0.039 |
| $\eta_s$  | Ellipticity of the FR cross section | 1.0  |
| $\alpha_s$ | Shape parameter for the leading edge | 2.5  |

Figure 7. Top panel shows distance measurements for the leading edge of the 2018 November 5 CME as a function of time based on images from LASCO/C2 (red squares) and LASCO/C3 (green diamonds). The $t = 0$ point on the time axis corresponds to UT 22:00 on November 4. These data points are fitted with a simple kinematic model assuming a constant acceleration phase followed by a constant velocity phase. The solid line is the best fit, and the bottom panel shows the inferred velocity profile.

Figure 8. Velocity is plotted vs. distance from Sun-center for the 2018 November 5 CME based on the kinematic model from Figure 7. This is compared with an average streamer blob kinematic profile based on measurements from Wang et al. (2000), and an average kinematic profile of Group 3 CMEs from Wood et al. (2017), which are CMEs with no associated solar surface activity. The dotted–dashed line marks the 1 au distance.

The streamer blobs and Group 3 CMEs have essentially identical kinematic profiles in Figure 8, involving a very slow acceleration that does not reach a terminal velocity until $\sim 30 R_e$. This behavior is widely assumed to be similar to that of the slow solar wind. In contrast, the 2018 November 5 transient reaches its peak speed of 439 km s$^{-1}$ by $\sim 7 R_e$. The transient is very much like previously studied streamer blobs in its general appearance and is clearly associated with the quiescent streamer structure. However, its kinematics are very unusual for streamer blobs, which were first defined by Sheeley et al. (1997). More recent surveys of the blobs also do not include any events that are so impulsively accelerated (Song et al. 2009; López-Portela et al. 2018). The only clear exceptions are blob-like ejections that follow CMEs (Song et al. 2012), but there is no CME precursor for the November 5 event.

5. Summary

We studied a small transient observed by PSP/WISPR on 2018 November 5, which is also seen in LASCO and COR2-A coronagraphic images from SOHO and STEREO-A, respectively. Our findings are summarized as follows:

1. Despite looking narrow and jetlike from 1 au, the WISPR images are very suggestive of an FR morphology, with a visible leg stretching back toward the Sun long after the leading edge of the transient has left the FOV.
2. Assuming an FR shape, we perform a 3D reconstruction of the small CME, representing the first such reconstruction considering both multiple 1 au vantage points and a viewpoint close to the Sun. Synthetic images from the reconstruction are reasonably successful at reproducing the CME appearance in the WISPR, LASCO, and COR2-A images.
3. A kinematic fit to measurements from LASCO images implies that the CME accelerates at a rate of about 45.3 m s$^{-2}$ to a terminal speed of 439 km s$^{-1}$, which it reaches at a distance of about 7 $R_e$ from Sun-center.
4. The small transient looks very much like a streamer blob in the coronagraph images from 1 au, but its kinematics are unusual, with a somewhat higher speed, and a much
faster acceleration. A more extensive observational study is necessary to determine whether the 2018 November 5 transient is representative of a class of streamer disconnection events that are clearly distinct from the streamer blobs studied in the past or if the event is best described as being simply a blob with anomalously impulsive acceleration.

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