Investigating the Cross Sections of Coronal Mass Ejections through the Study of Nonradial Flows with STEREO/PLASTIC

Nada Al-Haddad, Antoinette B. Galvin, Noé Lugaz, Charles J. Farrugia, and Wenyuan Yu
Space Science Center, Institute for the Study of Earth, Oceans, and Space, and Department of Physics and Astronomy, University of New Hampshire, NH, USA
nada.alhaddad@unh.edu

Received 2021 June 24; revised 2021 October 19; accepted 2021 October 20; published 2022 March 4

Abstract

The solar wind, when measured close to 1 au, is found to flow mostly radially outward. There are, however, periods when the flow makes angles up to 15° away from the radial direction, both in the east–west and north–south directions. Stream interaction regions (SIRs) are a common cause of east–west flow deflections. Coronal mass ejections (CMEs) may be associated with nonradial flows in at least two different ways: (1) the deflection of the solar wind in the sheath region, especially close to the magnetic ejecta front boundary, may result in large nonradial flows; and (2) the expansion of the magnetic ejecta may include a nonradial component, which should be easily measured when the ejecta is crossed away from its central axis. In this work, we first present general statistics of nonradial solar wind flows as measured by STEREO/PLASTIC throughout the first 13 yr of the mission, focusing on solar cycle variation. We then focus on the larger deflection flow angles and determine that most of these are associated with SIRs near solar minimum and with CMEs near solar maximum. However, we find no clear evidence of strongly deflected flows, as would be expected if large deflections around the magnetic ejecta or ejecta with elliptical cross sections with large eccentricities were common. We use these results to develop a better understanding of CME expansion and the nature of magnetic ejecta, and point to shortcomings in our understanding of CMEs.

Unified Astronomy Thesaurus concepts: Solar coronal mass ejections (310); Magnetic fields (994); Solar wind (1534); Interplanetary physics (827)

Supporting material: data behind figures

1. Introduction

Coronal mass ejections (CMEs) are large solar plasma eruptions that are dominated by the magnetic field. They occur frequently, especially near solar maximum conditions. They have been the subject of numerous studies since their initial discovery in 1971 (Tousey 1973). Following their first in situ observation, by five longitudinally spaced spacecraft in a rare conjunction event in 1979 (Burlaga et al. 1981), they have been considered as coherent structures. For a significant proportion of CMEs, their internal magnetic fields can be adequately described as twisted flux ropes (Gold 1962; Klein & Burlaga 1982; Burlaga 1988). Consequently, and mainly for simplicity, it was then assumed that CME cross sections were circular. Following that, several fitting techniques to estimate the magnetic field configuration from in situ observations have been developed, the vast majority of which assume a circular cross section (Lepping et al. 1990; Marubashi 1986; Farrugia et al. 1993; Nieves-Chinchilla et al. 2016). Alternatively, however, elliptical cross sections have also been proposed, based on the idea that as CMEs propagate, they deform, a process that is commonly referred to as “pancakeing.” Elliptical cross sections have also been proposed because the circular cross section was deemed to be a strong simplification that was made for the benefit of writing down simple analytical models, to which the natural extension is an elliptical cross section. To further account for the dynamic changes in the CME shape during propagation, Riley & Crooker (2004) and Owens & Crooker (2006), using a kinematics model, presented a scenario in which a CME starts as a flux rope with a circular cross section that evolves radially in heliocentric coordinates. In such a scenario, the circular cross section evolves kinetically into a convex-outward, bean-shaped ellipse, as can be seen in Figure 1.

Such a deformation is also typically observed in numerical simulations, especially for CME models that do not have internal magnetic fields, such as ENLIL (Odstrcil & Pizzo 1999), as well as for those initiated with flux ropes or spheromaks (Manchester et al. 2004; Channé et al. 2006; Shiota & Kataoka 2016; Scolini et al. 2019), albeit the deformation is not always as extreme. The elliptical cross section analytical fitting technique of Hidalgo et al. (2002) is an example of an early application of the concept of fitting elliptical cross sections to in situ measurements of CMEs, and this has more recently been revisited by Nieves-Chinchilla et al. (2018). In that work, a mathematical and fitting model is developed to take into consideration the elliptical cross section resulting from the interaction of a CME with the solar wind. Other works, such as Erdélyi & Morton (2009), have developed models of flux ropes with different elliptical cross sections for application to the propagation of magnetohydrodynamical waves inside flux ropes.

Statistical analyses of the in situ measurements of the distribution of impact parameters (the distance between the spacecraft path and the axis of the flux rope) of more than 100 CMEs by Lepping & Wu (2010) have been used by Démoulin et al. (2013) to deduce that the CME cross section is elliptical, with a ratio of minor axis (radial direction) to major axis (tangential or normal direction) of 1:2 or 1:3. Simultaneous measurements of magnetic ejecta (MEs) by Wind and ACE, when separated longitudinally by 0.01 au, have been found to be...
consistent with an elliptical cross section of similar eccentricity (Lugaz et al. 2018). Nieves-Chinchilla et al. (2018) showed an example of a CME measured in situ by Wind, for which the model with an elliptical cross section fits the magnetic field measurements significantly better than a model with a circular cross section.

The idea of an elliptical cross section has been taken further by Owens et al. (2017). Based on the widely accepted notion that the latitudinal extents of CMEs remain constant as they propagate (e.g., see Riley & Crooker 2004), the simple kinematic model of CME propagation explained earlier (Owens & Crooker 2006) results in the major axis becoming significantly larger than the minor axis, to the point that the latitudinal expansion speed becomes larger than the local Alfvén speed (see Figure 2 from Owens et al. 2017). Based on this, Owens et al. (2017) concluded that the CME becomes an incoherent structure at a heliocentric distance of 0.2–0.5 au, depending on its (fixed) latitudinal width. It is worth noting that such a model is purely kinematic, and does not account for the complex roles played by the various forces present in the CME (for a discussion of forces acting on CMEs as they propagate, see, e.g., Shen et al. 2012 and Kay & Nieves-Chinchilla 2021). In addition, such a model also places a constraint on the evolution of CMEs, ignoring major processes that impact CME shape, such as expansion, deflection, rotation, and erosion. To that effect, Suess (1988) illustrated a model of CME evolution from a circular to an elliptical cross section in a manner similar to that presented later by Riley & Crooker (2004), but highlighted how the effect of the magnetic tension must be strong enough to compensate for this deformation and to keep the cross section nearly circular.

One would expect these studies to have investigated the presence or absence of nonradial flows as a potential signature of the evolving ejecta shape. However, very few works up until now have touched on the nonradial flows associated with CMEs. For example, the model of Wang et al. (2016) represents CMEs with a circular cross section, and it uses the information provided by the three components of the velocity vector, along with the three components of the magnetic field vector, to simultaneously fit the CME magnetic field and velocity. This includes its radial propagation, any nonradial bulk motion as well as a uniform expansion to maintain the circular cross section. While nonradial flows are considered, the model is limited by its assumption of a circular cross section. Another example is Owens & Cargill (2004), who investigated the presence of large nonradial flows associated with CMEs. However, they focused on the flows associated with the CME sheath regions, as those tend to be larger than the nonradial flows inside ejecta. Quoting from their conclusion, the authors noted “the existence of significant nonradial flows in the body of ejecta, though the magnitude of such flows are nominally less than the preceding sheath region.” Except for these works, the nonradial flows inside CMEs have not been investigated or used in models to better reflect the CME elliptical cross section in a comprehensive manner.

In the present work, we study the nonradial plasma flows as measured near 1 au over solar cycle 24 in a comprehensive manner. In Section 2, we lay out the different scenarios in which a CME is expected to change size and shape as it propagates, and the associated flow signatures. In Section 3, we describe the data and the methodology used in this study, the initial statistical analysis, including the average nonradial flows measured each year during solar cycle 24, and their solar cycle variations. In Section 4, we perform an analysis on the larger instances of nonradial flows. We study their causes and investigate their associations with CMEs or stream interaction regions (SIRs), and also with the substructures inside the CMEs (i.e., ejecta and sheaths). In Section 5, we focus on those CMEs that have strong radial expansion flows, in order to determine whether they are associated with nonradial flows inside the ejecta. We discuss our results and conclude in Section 6.

2. Nonradial Flows: Model-dependent Expectations

While investigations of MEs have focused on magnetic field measurements, plasma measurements provide additional information about the magnetic configurations of the ejecta, to which little, if any, attention has been devoted. In this section, we discuss why some nonradial flows are expected to be present inside those MEs that are crossed away from their centers, and how their directions should give information about the shape of the ejecta. We present three scenarios based on past works. As CME radial expansion is well attested (Klein & Burlaga 1982; Suess 1988; Steinberg et al. 1984).
Farrugia et al. 1993; Lugaz et al. 2017), all scenarios include CME radial expansion. We emphasize that most of these works do not consider nonradial flows, but, as illustrated below, such flows should be present unless the circumstances are close to unique, as explained in the first scenario.

2.1. Scenario 1: Pure Radial Flows

This first scenario would explain the absence of nonradial flows. As CME lateral expansion is purely kinematic, it is not associated with bulk plasma motion away from the CME axis, i.e., it is a direct consequence of the purely radial propagation of the CME and of its maintaining a constant angular width (see Figure 2). However, since radial expansion and radial expansion flows are well attested, this scenario needs to explain why no expansion flows are measured in the nonradial direction. This could be because CME magnetic tension force acts in a way that limits and hinders expansion in the nonradial direction. However, because the solar wind is radially stratified, the nonradial expansion might in fact be of larger magnitude than the radial expansion, as there is no strong pressure gradient force hindering it. In this scenario, as illustrated in Figure 3, nonradial flows should be measured in situ when the CME is crossed away from its center. These nonradial flows are associated with CME expansion, have a magnitude of $V_{\text{exp}}$, and are directed away from the CME’s center. The net effect of the nonradial expansion combined with the kinematic expansion is to make the CME cross section highly elliptical.

2.2. Scenario 2: Elliptical Cross Section with Large Eccentricity

First, we note that the presence of radial expansion will have the effect of making the CME cross section more circular, unless there is also nonradial expansion. This has been previously discussed by Owens & Crooker (2006), for example. This occurs because the radial expansion partially compensates for the kinematically driven lateral expansion. However, as discussed above, radial expansion should be associated with nonradial expansion of at least a similar magnitude. Because the solar wind plasma is radially stratified, the nonradial expansion might in fact be of larger magnitude than the radial expansion, as there is no strong pressure gradient force hindering it. In this scenario, as illustrated in Figure 3, nonradial flows should be measured in situ when the CME is crossed away from its center. These nonradial flows are associated with CME expansion, have a magnitude of $V_{\text{exp}}$, and are directed away from the CME’s center. The net effect of the nonradial expansion combined with the kinematic expansion is to make the CME cross section highly elliptical.

2.3. Scenario 3: Elliptical Cross Section with Small Eccentricity or Circular Cross Section

As is clear from the discussions in the previous subsections, if MEs have circular cross sections near 1 au, there should be nonradial flows toward the center of the ejecta in order to maintain this circular cross section. These nonradial flows are needed to compensate for the kinematic distortion of the MEs. The most likely origin would be for these flows to be associated with the magnetic tension force, as first discussed by Suess (1988). In that work, the author argues that the interaction between the CME and the solar wind results in flows away from the center, in the radial direction, and flows toward the center, in the nonradial direction(s). These nonradial flows should only be measured when CMEs are crossed far from their center. These flows do not truly correspond to expansion, but result from the difference between the expected radial propagation of all points within a CME and the measured velocity needed to keep the cross section circular.

Figure 2. Schematic to illustrate scenario 1, associated with pure radial flows. The CME cross section is shown in red, starting from being circular with a half-angle of $\alpha$ and becoming elliptical farther away as it maintains its angular width, $2\alpha$. The propagation speed is $V_{\text{prop}}$ and $V_{\text{exp}}$ is the expansion speed, only in the radial ($r$) direction. This schematic follows the kinematics model of Riley & Crooker (2004).
These nonradial flows should reach values in excess of 100–200 km s$^{-1}$ for the CME cross section to remain circular (see Figure 4). Here, we follow the estimate of the nonradial separation speed as computed by Owens et al. (2017). This is the estimate of the separation speed between two points located on opposite sides of the CME outer boundary. In that work, the authors concluded that CMEs may be incoherent structures as the nonradial separation speed becomes greater than the Alfvén speed inside the CME.

A mixed scenario is possible for which the magnetic tension force is unable to fully counteract the kinematic distortion. However, for the CME to be less elliptical than the shape presented in scenario 1, nonradial flows toward the CME center/axis are required. If such flows are not present, the CME

---

**Figure 3.** Schematic to illustrate scenario 2, adapted from the (no tension) scenario in Figure 4 of Riley & Crooker (2004). $V_{\text{exp}}$ is assumed to be radial. $V_{\text{exp}}$ is assumed to be uniform in all directions. The actual CME shape should be similar to that discussed in Suess (1988) and Riley & Crooker (2004). In this scenario, the tangential flow (along t) should be directed away from the CME center/axis, resulting in nonradial flows. As such, the measured flow $V_{\text{measured}}$ has both radial and tangential components.

**Figure 4.** Schematic to illustrate scenario 3, adapted from Suess (1988). Magnetic ejecta are kinematically pushed to become elliptical, as illustrated by the dashed shape. $V_{\text{exp}}$ in the radial direction partially compensates for the kinematic effect. In addition, the tension force keeps the CME cross section circular. The result is that points far away from the CME center are observed to propagate toward the center with a nonradial speed $V_{\text{nr}}$. Note that this would mean that the CME angular size shrinks with distance.
cross section cannot be circular, and it should be at least as elliptical as found by the kinematic model.

In summary, since radial expansion is actually measured, it is nearly certain that nonradial flows should also be measured. Their directions shall inform us of (a) the shape of the CME ejecta; and (b) whether the radial flows are associated with the expansion or the restraining effect of the magnetic tension force. Therefore, investigating the nonradial flows as a CME is passing by a spacecraft should reveal significantly large flows in the plane perpendicular to the CME cross section. Even if these flows do not reach values as large as those predicted by Owens et al. (2017), such nonradial flows should reveal a great deal of information about the cross section of the CME. In addition, the absence of such flows would raise questions regarding the validity of the assumptions behind the above models.

3. Study 1: Statistics

3.1. Data Used and Methodology

We use plasma data measured by the Plasma and Suprathermal Ion Composition (PLASTIC) instruments (Galvin et al. 2008) on the twin Solar Terrestrial Relations Observatory (STEREO) spacecraft between 2007 and 2019. We use STEREO-A/PLASTIC 1 minute or 10 minute data, including north–south and east–west flow angles/speeds. The north–south flow angle is derived from the defectors on the electrostatic analyzer (ESA), which have a linear response and ±20° field of view, while the east–west flow angle is derived from a nonlinear response position anode with a nominal 45° field of view (which includes the velocity-dependent aberration angle). The east–west flow also has lower counting statistics. As such, the north–south flow is more accurately obtained.

For this initial statistical study, we use plasma data at a 10 minute resolution from STEREO-A only, as STEREO-B was lost in 2014, and therefore the STEREO-B data do not cover a full solar cycle. Using this data set, we have obtained the maximum and minimum flow angles and nonradial flow speeds for the whole period. In addition, the values of the following statistical quantities were obtained for each year: maximum, minimum, mean, median, standard deviation, and skewness. Data are plotted here in RTN coordinates, where R is radially outward from the Sun, T is along the cross-product of the Sun’s rotation axis and the R direction, and N is along the R × T direction, so that the R − N plane contains the Sun’s rotation axis.

3.2. Overall Statistics

The statistical results are shown in Figure 5. This illustrates that a large majority of the measurements are made within ±5° of the radial direction, and that there is no preference for a specific direction (as shown by the overall symmetric profiles). This indicates that the solar wind flows primarily radially outward. However, there are some deflected flows as high as 15° away from the radial both in the east–west and north–south directions. About 2% of the flows occur beyond 5° north or south of the ecliptic and ~11° away from the radial direction in the east–west direction. The wider distribution of flow angles away from radial in the east–west direction rather than the north–south direction may be related to the different ways in which they were measured, or it may be due to the fact that SIRs and corotating interaction regions (CIRs) are typically associated with relatively large deflections in the east–west direction (as described below).

The typical (i.e., most common) nonradial flows have low magnitudes, as seen in the bottom panel of the figure, with a peak in the distribution at around 10 km s\(^{-1}\), but also with a long tail going up to ~180 km s\(^{-1}\). More than 8% of the data points have nonradial flows above 50 km s\(^{-1}\), and about 1% have flows above 80 km s\(^{-1}\). For context, the average and median CME radial expansions in Solar Cycle 24, as measured by STEREO and reported by Jian et al. (2018), are 62 and 57 km s\(^{-1}\), respectively, so a nonradial flow speed of 80 km s\(^{-1}\) is larger than the radial expansion inside most CMEs.

Overall, this initial statistical survey indicates that relatively large nonradial flows have indeed been measured. In order to determine what their origin may be, we first turn to a more detailed statistical analysis of the variation of the maximum flow with year, as CMEs are more common in solar maximum and SIRs/CIRs in solar minimum. This is done to determine whether large nonradial flows occur in all phases of the solar cycle, or predominantly in solar minimum, as could be expected if large nonradial flows are associated mostly with SIRs/CIRs.

3.3. Solar Cycle Variation

We use 10 minute data from STEREO-A/PLASTIC and look at the yearly distribution of the nonradial flows. For each year, we determine the maximum, average, and median flow angles in the east–west and north–south directions, as well as the skewness of the distribution. The maximum value is noted irrespective of whether it occurs in the “positive” (north or east) or “negative” (south or west) directions. We use the flow angle rather than the flow speed as it removes any potential solar cycle variation due to changes in the average solar wind speed. Note that there is only limited data in 2015, due to STEREO-A being turned off during the superior solar conjunction.

Figure 6 shows the results. There is a clear solar cycle dependency in the maximum deflection flow angles measured for each year. The maximum deflection flow angles are larger close to solar maximum (2011–2015) than they are in solar minimum and the rising/declining phase of the cycle (from 2007–2009 and 2018–2019). 2010 and 2017 represent the two transition years between large sunspot numbers (and CMEs) in solar maximum and low numbers (i.e., a yearly sunspot number less than 10) in solar minimum. While not conclusive, this solar cycle variation gives us a hint that CMEs, which are much more common in solar maximum, may be associated with the largest deflection flows measured in the solar wind. In addition, CMEs were almost entirely absent during the deep solar minimum of 2007–2009, whereas there was still a significant number of SIRs. The maximum deflection flows in 2007–2009 of 10°–12° may therefore represent the maximum deflection made possible by a SIR/CIR. In comparison, the maximum deflection flows reached 13°–18° during the maximum phase of the solar cycle, and those flows may be more likely to be associated with CMEs. We look into large flows in more detail in the following section.

4. Study 2: Causes of Large Deflection Flows

Next, we identify the origins of all of the large nonradial flows (as characterized by Study 1) in terms of their associated structures (SIRs, CMEs, or others). We focus on the 24 events
for which the 10 minute flow angle is greater than 12° either in the east–west or north–south directions for STEREO-A. 12° has been chosen as the threshold for large flows based on the discussion in the previous section. Since there were no deflection angles of this magnitude in 2007–2009, nonradial flows of this magnitude are likely to be associated with CMEs. We use the CME and SIR databases of Jian et al. (2018) and Jian et al. (2019), respectively, to determine the association of these flows with specific structures. The proportions of the different categories are shown in Figure 7, and are as follows: 9 events correspond to CMEs, 1 of which is a compound event with an SIR; 10 events correspond to SIRs, 1 of which is the same compound event as mentioned before; and 6 events are not associated with CMEs or SIRs (sometimes because of the data gap). The compound event corresponds to an event that has the characteristics of a CME embedded within an SIR, an occurrence that is relatively frequent. Of the six events not associated with CMEs or SIRs, two of them occur in the trailing edge of a CME (within 4 hr of the CME end time). Fewer than half of the largest flows are in fact associated with CMEs. We now turn our attention to these cases and determine the circumstances.

4.1. Which CME Substructure Causes Large Nonradial Flows?

We first turn our attention to the maximum nonradial flow angle relating to a CME, which occurred between 2007 and 2019. This corresponds to the 2017 July 24 event, with a flow with an angle away from radial of 18°. Measurements by STEREO-A are shown in Figure 8. This is a CME with a strong magnetic field reaching above 60 nT at the back of the sheath and the beginning of the ME. There is a forward fast magnetosonic shock at 14:36 UT on July 24, with the ejecta starting at around 22:40 on July 24 and the strong magnetic field region lasting until 7:00 UT on July 25, although the CME end time is given as later in the database of Jian et al. (2018). The CME propagates through moderately fast solar wind, and
the sheath region is relatively complicated. The large nonradial flows (the blue line in the fourth panel) occur in the sheath region, first with strong northward flows until about 17:00 UT, and then with large southward flows (with the transition indicated by the dotted vertical line). These are consistent with draping (i.e., the wrapping of the magnetic field lines around the ejecta), as discussed by McComas et al. (1989), for example. The two distinct deflection flow patterns are separated by a discontinuity, where there are also temperature and density increases. There is no large deflection in the ME.

Next, we quickly consider the largest nonradial flow speeds that occur inside a CME (not plotted here). These are the nonradial flow speed values of 234 km s$^{-1}$ associated with the 2011 June 6 CME as measured by STEREO-A. This CME had a reported expansion speed of $\sim 100$ km s$^{-1}$. We identify the part of the CME where these large nonradial flows occurred. They correspond to deflection in the CME sheath associated with a complex event (potentially two separate flux ropes). There was a very long sheath region, where deflection was large. Overall, focusing on these two most extreme events, we confirm that CME sheaths are indeed associated with the largest deflection flows, confirming the suggestions of past studies, such as that of Owens & Cargill (2004). The question remains whether or not large deflection flows can be observed within the ME.

5. Study 3: CMEs with Large Radial Expansion Speeds

5.1. Data Selection and Methodology

We now turn our attention to CMEs with relatively large radial expansion speeds to determine whether or not any of them are associated with nonradial expansion flows. To perform this study, we look at all of the CMEs measured in situ by STEREO from 2007 to 2019 with radial expansions $> 100$ km s$^{-1}$. We use 1 minute PLASTIC data and the database of Jian et al. (2018). For each event with a radial expansion speed $> 100$ km s$^{-1}$, we calculate the average nonradial flow speed inside the ME (excluding the sheath) as well as the east–west and north–south flows. To do so, we average the nonradial flow speed over the duration of the ME, as provided by the database of Jian et al. (2018) (where the ME is referred to as a “magnetic obstacle”). We find 28 CME events for which the expansion speed is greater than 100 km s$^{-1}$ (excluding the 2012 July 23 event measured by STEREO-A, due to the extreme speed and the significant data gaps). We use this criterion of a radial expansion speed $> 100$ km s$^{-1}$ for the following reason: if nonradial flows are associated with CME expansions, then they should be easier to measure when a CME has a large radial expansion. Based on
the study by Démoulin et al. (2013), the median impact parameter inside magnetic clouds is $\sim 0.3$. If such clouds are crossed at an impact parameter of 0.3 or above, while expanding uniformly at speeds greater than 100 km s$^{-1}$, then the associated nonradial flows should be measurable. As we find 28 events satisfying this criterion, we can expect some CMEs to be crossed farther away from their centers than 0.3 (the average), which is a requirement for measuring nonradial flows under scenarios 2 and 3, as detailed in Section 2.

5.2. Statistics/Results

The average magnitude of the nonradial flow speeds over these 28 events is 40 km s$^{-1}$ (with a median of 36 km s$^{-1}$). This can be compared to the average radial expansion of 122 km s$^{-1}$ (with a median of 108 km s$^{-1}$), since both of these flows can be thought as occurring in the frame of the radially propagating ME. The ratio of nonradial to radial flows in the ME frame is about one third. Nonradial flows occur slightly more frequently in the tangential direction (with an average of 21 km s$^{-1}$ and a median of 13 km s$^{-1}$) than normal direction (with an average of 9 km s$^{-1}$ and a median of 7 km s$^{-1}$). There is no preferred north–south direction, but there is a slight preference for eastward flows (an average of $-8$ km s$^{-1}$).

The largest nonradial flows reach $\sim 70$ km s$^{-1}$, or about 60% of the average radial expansion flows as measured inside CMEs. As such, even though the magnitude of the nonradial flows is less than that of the radial flows that are associated with expansion in the ME frame, they are nonnegligible. However, to determine whether or not these nonradial flows play a role in CME expansion and shape, it is necessary to investigate their direction (either toward or away from the CME axis/center) in the frame of the ME, as explained through the various scenarios in Section 2.

Figure 8. The 2017 July CME event measured by STEREO-A and associated with the largest nonradial flow speed angle. The panels show the proton density, velocity, temperature, the north–south (blue) and east–west (red) flow angles, the nonradial flow speed, the magnetic field magnitude, and the three components of the magnetic field vector (red: radial; green: tangential; and blue: normal), from top to bottom. The solid vertical lines indicate the start of the CME sheath, and the start and end of the ejecta, respectively. The region of large deflection flows occurs in the sheath, ahead of the ME, and there is a reversal of the flow direction, from northward to southward, at the dotted line.
5.3. Case Studies

We focus on one case with relatively average nonradial flows, as well as one additional case with large nonradial flows.

5.3.1. The 2010 September 11 CME

Figure 9 shows the STEREO-A measurements of the 2010 September 11 CME. This is a relatively typical CME, which was preceded by a dense sheath region and a fast forward shock at 6:59 UT on September 11. The ME lasted for more than 36 hours, and was crossed at a high impact parameter (notice the large $B_R$ values in the last panel). The radial expansion is $\sim 110$ km s$^{-1}$, as calculated from the decreasing speed profile in the second panel. The average speed of the nonradial flows inside the ejecta is $\sim 40$ km s$^{-1}$, primarily in the eastward direction ($-T$), but with a component in the southward direction ($-N$) at the center of the ejecta (the peak of $\sim 30$ km s$^{-1}$ at around 07:00 UT on September 12). These nonradial flows reach $\sim 75$ km s$^{-1}$ in the front half of the ejecta (note that the very front part of the ejecta has almost zero nonradial flows). While there are even larger nonradial flows inside the front part of the sheath, the nonradial flows inside the ejecta are notable not only in terms of their magnitude, but also in terms of their consistent direction and decreasing magnitude as the CME passes over the spacecraft.

Next, we turn our attention to the orientation of the ME, and the direction of these nonradial flows with respect to the ejecta, to shed light on their relation to the three scenarios discussed previously.

A fit with the circular cross section force-free model of Lepping et al. (1990) is performed for the magnetic field measurements from September 11 16:45 UT to September 13 05:55 UT. This model was chosen because the requirements for using the static force-free model appear to be satisfied. While more complex models exist, we intend to confirm the overall orientation (i.e., whether it is low lying or highly inclined), and whether the crossing occurs at a small or large impact parameter. For this purpose, the well-validated model of Lepping et al. (1990) is appropriate. The orientation is found to be low-inclined, with $(\theta, \phi) = (-23^\circ, 254^\circ)$, the latitude and longitude angles of the flux rope axis with a negative chirality.

As such, this is a south–west—north (SWN) cloud (with $B_N$ varying from negative to positive, while $B_T$ remains negative). The impact parameter is confirmed to be high, at 0.75, with $B_R$ positive, especially in the front part of the ejecta. For such a low-inclined ejecta to be crossed at a high impact parameter, the nonradial flows associated with the ejecta cross section are expected to occur in the north–south direction (see the right panel of Figure 9). The southward-directed nonradial flows are consistent with this, following scenario 2, but their magnitudes only constitute up to 25% of the radial expansion flows, even though the impact parameter is high. The dominant nonradial flows in the $-T$ direction could be associated with a global expansion of the CME’s axis (not its cross section).
5.3.2. The 2012 July 11 CME

Figure 10 shows the STEREO-A measurements of the 2012 July 11 CME. The flow makes an angle of \(\sim 8\^\circ - 10\^\circ\) in the eastward direction throughout the ME, with an additional deflection of \(\sim 3\^\circ\) toward the north in the early part of the ejecta. Taken together, this corresponds to nonradial speeds reaching above 120 km s\(^{-1}\), which are comparable in magnitude to the radial expansion of the ejecta. As for the previous event, the radial component of the magnetic field is relatively elevated throughout the ME, possibly indicating a crossing away from the ME center, with \(B_R\) being especially large early in the ejecta, before decreasing in magnitude.

The magnetic field within the ME is not well organized, but a fitting is possible from 17:00 UT on July 11 to 06:00 UT on July 13 with the force-free circular cross section model of Lepping et al. (1990). The orientation is found to be low-inclined, with \((\theta, \phi) = (-20\^\circ, 94\^\circ)\), the latitude and longitude angles of the flux rope axis with a negative chirality. As such, this is a north–east–south (NES) cloud (with \(B_N\) varying from positive to negative, while \(B_R\) remains positive). The impact parameter is confirmed to be high, at 0.79. For such a low-inclined ejecta to be crossed at a high impact parameter, the nonradial flows are expected to occur in the north–south direction (see the bottom right panel of Figure 10). Since \(B_N\) is large at first, the initial flows in the northward direction indicate flows away from the center, consistent with scenario 2. However, even with a large radial expansion and a high impact parameter, the north–south flows are only a small fraction (\(\sim 20\%\)) of the radial expansion. The nonradial flows in the \(-T\) direction cannot easily be understood, except as a general deflection of the ejecta, or as a sign that the CME magnetic morphology is more complex than one with invariance along a central axis.

6. Discussion and Conclusions

Our expectations are that significant (>5\(^\circ\)) nonradial flows should be measured in association with the crossings of CME ejecta away from their centers (high impact parameters). These flows should occur in all of the following instances: (a) if the CME expansion, which is measured in the radial direction, is isotropic; (b) if the CME expansion is faster in the nonradial direction; and (c) if the magnetic field tension force keeps the CME cross section circular.

In the current study, we first looked at all of the statistics of nonradial flows as measured by STEREO/PLASTIC over the first 13 yr of its mission. We determined that nonradial flows that are comparable in magnitude to large radial expansion flows do occur. We then turned our attention to the solar cycle variation, finding clear signs that the maximum values of nonradial flow angles occur close to solar maximum, whereas solar minimum values do not go further than 10\(^\circ\)–12\(^\circ\) away from the radial direction. This indicates that CMEs, which are more common during solar maximum, may be associated with the largest flows.

We then turned our attention to those instances in which the nonradial flow angles reached values of 12\(^\circ\) or more, and found that \(\sim 40\%\) were indeed associated with CMEs; that about the
same number were associated with SIRs; and that the rest were not clearly associated with any transients. We then confirmed that the largest nonradial flows inside CMEs are associated with deflections in the sheaths.

In the final part of this study, we looked at the magnitudes of nonradial flows for CMEs with large radial expansion speeds measured by STEREO. We determined that the average nonradial flow speed inside 28 such events was 40 km s$^{-1}$, or about one third of the radial expansion speed. We looked at two events to determine the directions of these flows with respect to the orientation of the ejecta. In both cases, the flows occur primarily along the flux rope axis, and not in the direction of the CME cross section. In both cases, there are small flows consistent with small nonradial expansion, which would imply that a CME cross section is somewhat more elliptical than is implied by kinematic models, such as that of Riley & Crooker (2004). The presence of large nonradial flows in the direction of the CME axis cannot be easily explained. While in one of our case studies it could be understood as an expansion of the CME axis, in the other case, the flows are in the opposite direction. They might be associated with an overall deflection of the CME, although the absence of such flows in part of the sheath of the 2010 September 11 CME would mean that the sheath and the ME are not deflected in the same way. Instrument effects may be at play, especially since the flows along the normal direction (north–south) are measured through deflectors, whereas the flows along the tangential direction (east–west) are derived from impacts on the microchannel plates.

Overall, a surprising result of this investigation is that there are no steady large nonradial flows inside CME ejecta, as would be expected from uniform expansion or the effect of the magnetic tension force. As discussed in Section 2, this can only be understood if the radial expansion is not associated with an expansion in the nonradial direction, and if the CME cross section becomes highly elliptical due to kinematic effects. Alternatively, the entire paradigm of a flux rope with an axial invariance might be too limited (see the previous discussion in Al-Haddad et al. 2011). Multispacecraft measurements that include plasma measurements may provide an opportunity to further investigate this problem. They will be more likely in the near future as STEREO returns to the vicinity of the Sun–Earth line while solar activity picks up. Nonetheless, such multispacecraft measurements may not always be able to help distinguish between different CME structures (Al-Haddad et al. 2019).

This research was supported by NASA Science Mission Directorate (SMD) grants 80NSSC21K0463, 80NSSC20K0431, 80NSSC17K0556, and 80NSSC20K0700, and NSF grant AGS1954983.

**ORCID iDs**

Nada Al-Haddad @ https://orcid.org/0000-0002-0973-2027
Antoinette B. Galvin @ https://orcid.org/0000-0003-3752-5700
Noé Lugaz @ https://orcid.org/0000-0002-1890-6156
Charles J. Farrugia @ https://orcid.org/0000-0001-8780-0673
Wenyuan Yu @ https://orcid.org/0000-0002-2917-5993

**References**

Al-Haddad, N., Poedts, S., Roussev, I., et al. 2019, ApJ, 870, 100
Al-Haddad, N., Roussev, I. I., Mostl, C., et al. 2011, ApJL, 738, L18
Burlaga, L., Sittler, E., Mariani, F., & Schwenn, R. 1981, JGR, 86, 6673
Burlaga, L. F. 1988, JGR, 93, 7217
Chávez, E., van der Holst, B., Jacobs, C., Poedts, S., & Kimpe, D. 2006, A&A, 447, 727
Démoulin, P., Dasso, S., & Janvier, M. 2013, A&A, 550, A3
Erdélyi, R., & Morton, R. J. 2009, A&A, 494, 295
Farrugia, C. J., Burlaga, L. F., Osherovich, V. A., et al. 1993, JGR, 98, 7621
Galvin, A. B., Kistler, L. M., Popecki, M. A., et al. 2008, SSRv, 136, 437
Gold, T. 1962, SSRv, 1, 100
Hidalgo, M. A., Nieves-Chinchilla, T., & Cid, C. 2002, GeoRL, 29, 1637
Jian, L. K., Luhmann, J. G., Russell, C. T., & Galvin, A. B. 2019, SoPh, 279, 31
Jian, L. K., Russell, C. T., Luhmann, J. G., & Galvin, A. B. 2018, ApJ, 855, 114
Kay, C., & Nieves-Chinchilla, T. 2021, JGRA, 126, 2020JA028911
Klein, L. W., & Burlaga, L. F. 1982, JGR, 87, 613
Lepping, R. P., Burlaga, L. F., & Jones, J. A. 1990, JGR, 95, 11957
Lepping, R. P., & Wu, C. C. 2010, AnGeo, 28, 1539
Lugaz, N., Farrugia, C. J., Winslow, R. M., et al. 2018, ApJL, 864, L7
Lugaz, N., Temmer, M., Wang, Y., & Farrugia, C. J. 2017, SoPh, 292, 64
Manchester, W. B., Gombosi, T. I., Roussev, I., et al. 2004, JGRA, 109, 1102
Marubashi, K. 1986, AdSpR, 6, 335
McComas, D. J., Gosling, J. T., Bame, S. J., Smith, E. J., & Cane, H. V. 1989, JGR, 94, 1465
Nieves-Chinchilla, T., Linton, M. G., Hidalgo, M. A., et al. 2016, ApJ, 823, 27
Nieves-Chinchilla, T., Linton, M. G., Hidalgo, M. A., & Voorlind, A. 2018, ApJ, 861, 139
Odstrcil, D., & Pizzo, V. J. 1999, JGR, 104, 483
Owens, M., & Cargill, P. 2004, AdvGeo, 22, 4397
Owens, M. J., & Crooker, N. U. 2006, JGRA, 111, A10104
Owens, M. J., Lockwood, M., & Barnard, L. A. 2017, NatSR, 7, 4152
Riley, P., & Crooker, N. U. 2004, ApJL, 600, 1035
Scolini, C., Rodríguez, L., Mierla, M., Pomoell, J., & Poedts, S., 2019, A&A, 626, A122
Shen, F., Wu, S. T., Feng, X., & Wu, C.-C. 2012, JGRA, 117, A11101
Shiota, D., & Kataoka, R. 2016, SpWea, 14, 56
Suess, S. T. 1998, JGR, 93, 5437
Tousey, R. 1973, BAAS, 5, 419
Wang, Y., Zhuang, B., Hu, Q., et al. 2016, JGRA, 121, 9316