A FULL STUDY ON THE SUN–EARTH CONNECTION OF AN EARTH-DIRECTED CME MAGNETIC FLUX ROPE

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ABSTRACT

We present an investigation of an eruption event of a coronal mass ejection (CME) magnetic flux rope (MFR) from the source active region (AR) NOAA 11719 on 2013 April 11 utilizing observations from the Solar Dynamic Observatory, the Solar Terrestrial Relations Observatory, the Solar and Heliospheric Observatory, and the WIND spacecraft. The source AR consists of a pre-existing sigmoidal structure stacked over a filament channel which is regarded as an MFR system. EUV observations of low corona suggest further development of this MFR system by added axial flux through tether-cutting reconnection of loops at the middle of the sigmoid under the influence of continuous slow flux motions for two days. Our study implies that the MFR system in the AR is initiated to upward motion by kink instability and further driven by torus instability. The CME morphology, captured in simultaneous three-point coronagraph observations, is fitted with a Graduated Cylindrical Shell (GCS) model and discerns an MFR topology with its orientation aligning with a magnetic neutral line in the source AR. This MFR expands self-similarly and is found to have source AR twist signatures in the associated near-Earth magnetic cloud (MC). We further derived the kinematics of this CME propagation by employing a plethora of stereoscopic as well as single-spacecraft reconstruction techniques. While stereoscopic methods perform relatively poorly compared to other methods, fitting methods worked best in estimating the arrival time of the CME compared to in situ measurements. Supplied with the values of constrained solar wind velocity, drag parameter, and three-dimensional kinematics from the GCS fit, we construct CME kinematics from the drag-based model consistent with in situ MC arrival.

Key words: solar–terrestrial relations – Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: filaments, prominences – Sun: heliosphere – Sun: magnetic fields

1. INTRODUCTION

Coronal mass ejections (CMEs) are magnetically driven gigantic events whose disturbance in the outer corona influences space weather to a wide range. When propagating from the Sun, they appear to have three-part structures in white light (Illing & Hundhausen 1985; Burlaga 1988; Forsyth et al. 2006) with a leading edge, core, and cavity. Although it is not quite clear in observations, the cavity is supposed to have connections in the source regions on the Sun and is approximated by a coherent, large-scale magnetic magnetic flux rope (MFR), manifested by twisted magnetic field lines. A recent statistical study suggests that at least 40% of CMEs observed by space-borne instruments have a clear MFR structure (Vourlidas et al. 2013). Many studies from space- and ground-based observations suggested that this MFR structure in the outer corona is an evolved form of filaments seen in Hα or sigmoidal structures in soft X-rays in the so-called magnetic active regions (ARs; e.g., Lepping et al. 1990; McKenzie & Canfield 2008; Cheng et al. 2012; Howard & DeForest 2012; Vemareddy et al. 2012; Zhang et al. 2012) on the Sun. Central to the space weather phenomena and the Sun–Earth connections of the CMEs having signatures of this predicted MFR topology, a majority of past and current scientific research focuses on basic questions like how such MFR-like structures formed or came into existence (e.g., Pneuman 1983; van Ballegooijen & Martens 1989; Leka et al. 1996; Fan 2001; Fan & Gibson 2004; Gibson et al. 2004, 2006), what are the initiating conditions in the source AR (e.g., Martin et al. 1985; Antiochos et al. 1999; Moore et al. 2001; Priest & Forbes 2002; Lin et al. 2003; Forbes et al. 2006; Kliem & Török 2006; Fan & Gibson 2007; Chen 2011; Cheng et al. 2012; Vemareddy et al. 2012; Vemareddy & Zhang 2014), and what kind of MFR evolution drives its outward propagation (e.g., Gopalswamy et al. 2000, 2001; Vršnak & Gopalswamy 2002; Forsyth et al. 2006; Manoharan 2006; Davies et al. 2009; Webb et al. 2009; Temmer et al. 2011, 2012; Harrison et al. 2012; Vršnak et al. 2013) in the extended corona and interplanetary medium.

Two main ideas that the past and current observations on the Sun implied were the emergence of the MFR from beneath the inner photosphere and the formation of the MFR from sheared arcade. In the process of AR formation, while it emerges, the MFR structure would emerge as a bipolar region and equilibrate with the overlying pre-existing structure (Fan 2009). Numerical simulations of the bodily emergence of the MFR (Fan 2001; Fan & Gibson 2003; Magara 2001; Gibson et al. 2004; Okamoto et al. 2009; Lites et al. 2010) showed the formation of the sheared arcade in the corona after the MFR axis reached the photosphere. In the case of a fully emerged AR, the equilibrated MFR structure in the form of a sheared arcade evolves into a full fledged MFR. Based on these ideas, different theoretical and observational models have been proposed and constructed (Antiochos 1998; Antiochos et al. 1999; Lin et al. 2003; Forbes et al. 2006; Kliem & Török 2006; Fan & Gibson 2007; Chen 2011). In all of them, twisted MFR or sheared arcade, which is a source of magnetic helicity, is the basic ingredient of pre-eruptive magnetic configuration. Pneuman (1983) showed how helical MFRs can be formed by reconnection in a sheared coronal arcade. During the progressive reconnection phase, the magnetic flux gets canceled, transforming the magnetic field lines in the sheared arcade along the magnetic inversion line to winding helical
field lines about a common axis of nearly formed MFR (Green & Kliem 2009; Green et al. 2011). Later, van Ballegooijen & Martens (1989) proposed a mechanism for the formation of helical field lines from the reconnection of a less sheared arcade along the polarity inversion line and also to build up the MFR. The submerging motion of fluxes about the polarity inversion line (PIL) also plays a vital role in bringing less sheared arcades to highly sheared arcades. The reconnection location is usually associated with the photospheric flux cancellation (Yurchyshyn & Wang 2001; Bellot Rubio & Beck 2005) and is evidently reported to be involved with the MFR formation and its eruption (Green et al. 2011).

In the low corona, triggering and driving the MFR eruption is another important step in the eruption process. Filament, prominence, or sigmoid eruptions modeled by the numerical and theoretical constructions of MFRs have been successful in many aspects of observed eruption features. The physics of these models is essentially based on the loss of equilibrium of the MFR after reaching a critical height (Forbes & Isenberg 1991; Priest & Forbes 2002), kink instability caused by exceeding the MFR’s twist (Török et al. 2004; Török & Kliem 2005), and the torus instability (Kliem & Török 2006; Aulanier et al. 2010) of the MFR when there is a rapid decline of the background field in the direction of the expansion of the MFR.

In the case of source ARs located near the disk center, the CME MFR eruption is very likely directed toward the Earth, which has a direct impact on space weather. In order to estimate the arrival times of CMEs to Earth, a vital step is to understand the kinematic evolution of CMEs while propagating through the heliosphere. Based on the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) coronagraph (COR) observations on board the Solar and Heliospheric Observatory (SOHO), many studies found that CMEs with high speeds near the Sun decelerate during the journey to the Earth while CMEs with slow speeds accelerate (Lindsay et al. 1999; Gopalswamy et al. 2000, 2001; Yashiro et al. 2004; Manoharan 2006). This finding clearly emphasizes the interaction of CMEs with the ambient solar wind medium. LASCO observes only out to 30 $R_\odot$ and can provide only the projected kinematics of a CME while the CME speed changes significantly beyond the field of view (FOV) of CORs. Therefore, two-point measurements of speed, one near the Sun and another near the Earth, are not sufficient to fully capture the physics of CME evolution in the heliosphere.

In the present era, the estimation of CME kinematics from its lift-off in the low corona to the Earth or even beyond is possible with multiple views (A and B) of the Sun–Earth space from the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008). Using CORs and heliospheric imagers (HIs) of the Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al. 2008) on board STEREO, several studies have been carried out attempting to associate remote imaging observations with in situ observations near the Earth (Davies et al. 2009; Liu et al. 2010; Möstl et al. 2010; Harrison et al. 2012; Lugaz et al. 2012; Temmer et al. 2012; Mishra & Srivastava 2013; Liu et al. 2014a; Rollett et al. 2014; Möstl et al. 2015). Single and/or multiple spacecraft reconstruction methods on HI observations have shown major limitation in estimating kinematics and the inherent difficulties involved in interpreting the HI observations of the CMEs. However, most of these studies have been carried out mainly for Earth-directed CMEs while the STEREO separation was small. Therefore, tracking the CME or its associated MFRs moving away form the observer seems to be rarely undertaken for study (Liu et al. 2014b). Hence, the assessment of the relative performance of reconstruction methods with different geometry, assumed for a CME receding from the observer, is an obvious next step for the solar–terrestrial scientist.

In the present study, we focused on an eruption event on 2013 April 11 from the NOAA AR 11719, uniquely involving its gradual build up and eventual eruption as an Earth-directed CME. The initiation mechanism based on morphological twist signatures of this MFR event was extensively studied in Vemareddy & Zhang (2014, hereafter VZ14). Interestingly, the solar energetic particle (SEP) event on 2013 April 11 was found to originate from this eruption event (Lario et al. 2014) which produced the first large Fe-rich SEP event of solar cycle 24 (Cohen et al. 2014). In view of the Sun–Earth connection of this CME MFR event, in this manuscript, we extended the study of VZ14 on the formation or development scenario of the MFR in the source AR and its propagation in the inner heliosphere after its eventual eruption from the source AR. Utilizing detailed multi-wavelength EUV observations from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012), we study the evolution history of the source AR three days prior. In concurrent with the observed morphological evolution, we analyzed vector magnetograms obtained from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) to support or revert the scenario of MFR formation by canceling magnetic flux in the source AR. Moreover, taking advantage of multi-view observations from STEREO/SCCHI and SOHO/LASCO CORs, we determined the orientation of the underlying MFR by a parametrized fitting model to the observed white light CME morphology. We further tracked this CME, which is moving away from the STEREO observer, and estimated its kinematics using stereoscopic and single-spacecraft reconstruction methods. The estimated arrival time of the CME MFR at L1 is discussed in comparison with in situ plasma parameters to assess the reliability of the employed tracking methods. CME kinematics are also derived and discussed using a drag-based model (DBM). Furthermore, the AR twist signatures are explored from in situ magnetic field observations of this CME-associated magnetic cloud (MC). Such a study involving multi-scale observations examines the complete Sun–Earth connection of an event and furthers the understanding of space weather phenomena.

The manuscript is structured as follows: in Section 2, the requirements of observations from various instruments are outlined, and in Sections 3–4, the formidable conditions for the formation/development are explored using coronal EUV and photospheric magnetic field observations. For completeness, the details of the onset and driving mechanisms of this MFR eruption (VZ14) are given in Section 5. The orientation of the MFR while expanding from the source AR is determined in Section 6. Its propagation kinematics toward Earth and interplanetary twist signatures are presented in Section 7. We concluded with a summarized discussion of this investigation in Section 8.
2. OUTLINE OF OBSERVATIONS

The overall eruption event of our interest is outlined in Figure 1. The observations of the source AR NOAA 11719, both at photospheric and low corona heights, are well covered by the Solar Dynamic Observatory (SDO) and its component instruments AIA and HMI. Using AIA channels, especially 304 and 94 Å observations (0.6 arcsec pixel$^{-1}$), the pre-eruptive AR at 06:50 UT magnetic flux system presents an inverse S sigmoidal structure (top left panel) that is stacked over filament channels. During the initial upward rise motion at 06:15 UT (just before the main eruption around 06:55 UT), the plasma emission (in 131 and 94 Å observations) along this sigmoidal structure supports the interpretation that the sigmoid is manifested by a coherent core twisted flux system surrounded by a twisted overlying flux bundle (VZ14). We regard this coherent core flux along the sigmoid as the main body of the MFR, which is wound by the overlying flux bundle. The time difference image of 193 Å (top right panel) shows an EUV disturbance in the low corona during this main phase of eruption. This EUV disturbance also shows that the expanding

Figure 1. Top left: composite image of the solar disk prepared from the AIA 304 and 94Å observations. The source region of the CME on the Sun is marked with a rectangular inset. The pre-eruptive AR 11719 consisted of a sigmoidal structure that deviates from the filament channel. Top right: difference image (07:12–07:03 UT) of AIA 193 Å that indicates the EUV disturbance and outlines the rapidly expanding MFR from AR11719. Bottom left: propagating CME and bright leading edge in the C2 field of view on board SOHO. Image of the Sun from the AIA 193 Å observation is also placed at the occulter disk position. Bottom right: time profile of the GOES X-ray flux in the low- and high-frequency bands. The peak flux corresponds to the M6.5 flare that commenced at 06:55 UT (vertical green line) subsequent to the onset of the MFR at 06:15 UT (dashed gray vertical line). The red vertical line indicates the time of the captured C2 image shown in the left panel.
MFR has legs rooted from the pre-determined (“+”) sigmoid legs. The eruption of the sigmoid MFR from the low corona is preceded by a GOES M6.5 flare (bottom right panel). Importantly, its CME-driven shock propagates at high altitudes above the solar surface and was likely the source of the SEPs observed near Earth (Cohen et al. 2014; Lario et al. 2014).

This propagating CME in the outer corona was well observed by LASCO (Brueckner et al. 1995) on board SOHO and by SECCHI on board STEREO (A and B). The CME structure emerged out of the occult to become a halo-like structure at around 08:30 UT. Figure 1 (bottom left) of the LASCO/C2 image discerns a bright annular structure on the east limb of the disk resembling the leading edge followed by the invisible cavity of the MFR. While expanding, the transit of the MFR through multiple heights, in the FOVs of COR1 (1.1–4$R_\odot$), COR2 (2–15$R_\odot$), LASCO/C2 (1.5–6$R_\odot$), LASCO/C3 (3.5–30$R_\odot$) situated at perspective viewing angles, uniquely show a direct connection between the heliopheric MFRs and the sigmoidal structures in the source AR (more details in Section 6). The majority of observed CMEs in the past solar cycle had clear MFR structures and no presently known physical mechanism can produce a large-scale fast eruption beyond 10$R_\odot$ without ejecting an MFR (Vourlidas et al. 2013). Having these supporting observational signatures of MFR topology in both the source region sigmoid and the CME morphology, we use the term MFR while describing and interpreting the observations in its favor. The CME propagation in the heliosphere was tracked by the HI1/HI2 instruments of SECCHI. In situ plasma and magnetic field observations are obtained from the WIND space mission. Taking advantage of these detailed observations, we focus on the objectives mentioned in the last section.

3. DEVELOPMENT OF THE MFR STRUCTURE: AIA OBSERVATIONS

AR 11719 contains a well observed filament from its appearance on the eastern limb of the solar disk. The filament consists of two sections which together give cause it to have an inverse S-shape. These coronal features are identified to be associated with magnetic regions (labels in Figure 4(a)) at the photosphere. The lower section originates from the main sunspot (S1) and has a cusp shape at the joining to upper section. Long coronal loops with footpoints from flux region S2 are well captured in AIA passbands, predominantly in 171 Å and are observed to overly the filament, with conjugate footpoints lying in N1. In hotter passbands (2–10 MK) of the AIA, especially in 94, 131 Å, the entire AR structure becomes complicated as further features of loops filled with hot plasma are observed. However, the surrounding structures from other parts of the flux regions have similar thermal conditions. The field line system around the main filament is not quite enough to reveal the underlying topological configuration in detail. Because this entire configuration evolves under quasi-static conditions, we observe no significant large-scale structural change for hours.

The AIA filter passbands have a wide range of visibility of thermal plasma from the chromosphere (Log $T = 10^4$ K) to the hot, diffused corona ($\approx 10$ MK). In order to disclose details of the connection between the low-lying filament and the overlying loops (OL), we make use of the composite images of different combinations prepared from the AIA passbands. For a simultaneous view of the corona from the chromosphere, we showed in Figure 1 (top left) the 304 Å passband image at 06:50 UT on 2013 April 11 blended with the image of the 94 Å passband at the same time. From this, it is obvious that the low-lying filament channel in 304 Å deviates in projection with the overlying hot sigmoid. The filament, the sigmoid above it, and the overlying flux bundle demonstrate complex flux systems stacked over each other.

A similar observational view persists well before, on April 9, in the 304, 131, and 171 Å channels (Figure 2). The cool filament channel is overlaid by long plasma loops (OL) with their photospheric connections on either side of it. This is analyzed in successive composite frames prepared from 304, 171, and 94 Å (as shown in second row panels of Figure 2). The central part of the filament is increasingly surrounded by hot plasma illuminated in 131 Å, which indicates the augmenting scenario of the main body of the MFR by wrapped field lines. This would likely be due to reconnection in the current sheets formed in the interface of MFR and surrounding field, by which the thermal energy heats the plasma to observable temperatures (Gibson et al. 2006).

The observations are of three-dimensional structures projected onto the plane of the sky. Moreover, although the plasma and field are frozen together in a highly conducting corona so that coronal plasma structures essentially trace the magnetic field, plasma emission is the only possible distinct observable under certain density and temperature conditions dictated by an observing instrument. In this case, we made use of composite images prepared from different combinations of the AIA channels (for quiet and flaring corona with combinations 94, 335, 193 Å; flaring corona, chromosphere, and transition region in combinations of 131, 94, 304 Å) for our interpretations. They provide substantial evidence for the developing scenario of the sigmoidal structure during the three days of evolution (images not shown here).

The augmentation scenario of the MFR appears to occur in two stages (Figure 2). In the first stage, the long OL, in the form of an arcade, significantly turns to the sheared arcade and then transforms toward the east and west lobes of the sigmoid structure. In the second phase, these increasingly inclined loops turn toward two inverse J sections with footprints lying beside (L1 and L2) the filament. Evidently, loops L1 and L2 reflect a probable involvement in traditional tether-cutting reconnection (Moore et al. 2001). Once the reconnection of these L1 and L2 loops occurs, the formation of a continuous sigmoid is inevitable, by added axial flux tubes. These two phases possibly occur in a slow dynamical evolution, where infinitesimal displacements of the flux regions with these loops induce continuous reconnection, which adds twisted flux threads winding some common axis of the existing MFR. This mechanism therefore is identical to the sheared arcade to rope transformation proposed by van Ballegooijen & Martens (1989). Indeed, the observed magnetic flux distribution well supports this augmentation scenario which shows the canceling and approaching opposite flux patches side by the filament (Figure 4). Our interpretations are further supported by another set of observations (Figure 3) below.

Earlier on April 9 (Figure 3), the existence of the sigmoidal structure is not clear in hot channels except faintly observed filament channel. However, emission from the lower lobe section (like inverse J) is conspicuously present most of the time. After a day of evolution, i.e., by April 10, a developing sigmoidal structure becomes apparent with a visible east lobe.
Specifically, the hot overlying flux bundle at the middle of the sigmoid and its geometric evolution is of interest (VZ14). While undergoing dynamical evolution, this whole structure brightens intermittently, probably corresponding to small-scale reconnections of the loop systems. One such major bright emission corresponds to a partial/failed eruption (around 18:00 UT on April 10) in which the MFR lifted and appears to split so that the upper part expels and lower section settled back to its stable position (Gilbert et al. 2001, 2007). Data gaps around this period constrain to reveal more details on this partial eruption. After this, the two J-shaped sections merged to form a continuous sigmoidal MFR which is very apparent (panels at 15:00/10, 01:00/April 11). By this time, the magnetic flux distribution shows a fragmented and disappearing positive flux corresponding to the northern lobe structure of the MFR.

Furthermore, during the three days of evolution, it is difficult to interpret the magnetic topology of this flux system of filament/sigmoid from the projected imaging information. Bald patch separatrix surfaces (BPSS) and hyperbolic flux tubes (HFT) are two kinds of topological configurations associated with theoretically predicted MFR models (Titov et al. 2002). As suggested by van Ballagooijen, sigmoids formed from sheared arcades by photospheric flux cancellation driven by converging motions, which is the case here, are more likely associated with BPSS rather than HFT. When the sigmoid structure is regarded as an MFR lying low in height, its middle section dips into the dense photosphere and appears as two J sections in the coronal observations like X-ray or EUV. However, the associated BPSS topology may turn into HFT while the slow upward rise motion commences (Gibson et al. 2006) and the continuous structure of the MFR will be envisioned. Because fast reconnection occurs in a thinning current sheet with HFT, the MFR lifts off the filament completely with a full eruption and it is very unlikely for the eruption to be suppressed at that stage.

4. THE CANCELLATION OF MAGNETIC FLUX AND THE BUILD UP OF TWIST: HMI OBSERVATIONS

The corresponding details of the evolution of magnetic fields at the photospheric surface are studied (see Figure 4) by vector magnetic field observations. As explained earlier, the magnetic flux regions show little evolution during the three days with respect to their motion. The time evolution of the area integrated flux shows details about the change in the flux content. Indeed, the time profile of the absolute flux in the AR (Figure 5, top panel) indicates a continuous decrease of the magnetic flux from April 9 until the eruption onset on April 11. During this period, the north polarity flux (south polarity) decreased by 56% (48%) from its initial value at the early hours on April 9. This decay or decrease includes polarity regions having flux rope legs and the OL. Note that these profiles have 12 hr periodic variations probably related to the orbital effects of the HMI instrument which introduce variations in the field.
measurements both spatially and temporally (Hoeksema et al. 2014).

As the time duration is about two days over which this significant decrease of the fluxes observed, it is likely related to the general evolution of the AR in addition to slow reconnection and implies the usual scenario in decaying ARs. Furthermore, to identify the size distribution of these fluxes, we overlaid the contours of ±120 G. From snapshots of three
successive days, all identified magnetic regions evolve with decreasing spatial distribution of flux. Since one of the legs of the MFR is associated with the positive flux region N1 and N2, we isolate them (yellow contour) and measured the flux content at different snapshots (Figure 2). Consistent with the smearing flux distribution within this contour region, the measured net positive flux (see Table 1) decreases from $4.27 \times 10^{21}$ Mx on April 9 to a significant value of $1.98 \times 10^{21}$ Mx on 2013 April 11. A similar measure of the main sunspot flux from which the MFR originated implies the same conclusion.

These evolving conditions of fluxes support the sustainability and further development of the MFR. Because the MFR channel is already formed well before the observation on April 9, under the slow motions of the flux regions that are mostly driven by granular motions, reconnection of the field lines will reinforce the MFR by added axial flux. Field lines connecting sunspot S1 to N1 possibly reconnect in a traditional tether-cutting fashion (Moore et al. 2001) at the polarity inversion line with those connecting S2 and N2. However, those branches of field lines overlying the MFR from S2 to the diffused patch of N2 provides downward tension force to balance the upward force of the MFR due to the enhanced currents developed by the continuously added axial flux. For the occurrence of a successful eruption, the force balance should be lost either by weakening the overlying flux or by strengthening the axial flux in the MFR. Based on the observations, we argue that both of them could be conducive factors. As described earlier, the overlying flux bundle exhibits kink rise motion, which might allow for the initiation. The kink rise motion of the flux bundle signifies an increasing twist, which means enhanced currents and more axial flux in the MFR, supporting the second argument for force imbalance. In the absence of accurate twist measurements at the flux rope leg, the first argument is the most reasonable to consider under the action play. Looking at this point, parametric and numerical studies (Amari et al. 2010; Aulanier et al. 2010) suggest a limiting value of the axial flux of the rope ($6\%$–$10\%$) in the AR flux, beyond which force balance is lost. In decaying ARs, this value is in the range of $10\%$–$14\%$ (Bobra et al. 2008; Savcheva & van Ballegooijen 2009; Su et al. 2009). In our case, although it is difficult to separate these fluxes, for a quantitative approximation the axial flux of the rope ($6\%$–$10\%$) in the AR flux manifests overlying poloidal flux. So, these results delineate the marginal stability conditions for the MFR.

In order to further support the scenario of the formation or development of the flux rope, we compute the parameter

$$
\alpha_{av} = \frac{\sum J_y(x,y)\text{sign}\left[B_z(x,y)\right]}{\sum |B_z|}
$$

as a proxy for twist of ARs. It is derived from the assumption of force-free magnetic fields and signifies the extent of the twist of field lines due to field-aligned currents. The error in $\alpha_{av}$ is
error limit is much smaller than the mean value. Note the negative sign of $\alpha_{av}$ implies a left-handed helicity consistent with that of the inverse S sigmoid. The twist parameter has no corresponding evolution with the decreasing flux until April 11. It increased on April 9 following a gradual decrease on April 10. Then it commences increasing from April 11 until 15:00 UT to a value of $-2.3 \times 10^{-8} \text{ m}^{-1}$. Together, the decreasing flux content in the AR and the increasing average twist prominently from April 11 characterize the conditions to augment the existing sigmoidal structure as inferred from EVU observations.

5. THE ERUPTION MECHANISM

At the time of eruption, the source AR contains a filament as seen in the cool temperatures of AIA/304 Å, and over which a main inverse S-shaped sigmoid and multiple twisted flux bundles are visible in the AIA hot passbands, mainly 131 and 94 Å (last panel in Figures 2 and 3). Interpreting this sigmoid system in terms of MFR models, the initiation mechanism together with morphological, thermal, kinetic, and magnetic properties of this eruption event was studied in great detail by VZ14. This sigmoidal MFR starts with a slow rise from 06:15 UT followed by fast rise from 06:40 UT and eventual eruption. Consistent with our observational signatures of the development of the MFR over days, the results of their study suggest that the cancelling fluxes are prime factors to the monotonous twisting of the FR system reaching a critical state to trigger kink instability. The support for this instability comes from the observed kink-like evolution of the overlying flux bundle (Figure 3 and also Figure 2 in VZ14) and the co-spatial localized distribution of increased twist parameter in the main sunspot from where the MFR originated. This instability likely initiates the rise motion until a critical height for a possible onset of torus instability, from which the MFR likely undergoes self-similar expansion and outward propagation, subsequently resulting in the eventual eruption of an Earth-directed CME. Note that the analysis is based on MFR insertion model (Table 1), and the net positive flux (as a proxy for axial flux) over time indicates marginal stability for this MFR system. The preceding flare of GOES M6.5/3B class (from 06:55 UT; see Figure 1(d)) is a consequence of progressive reconnection in the thinning current sheet underneath the rising FR.

6. THE ORIENTATION OF THE CME MFR IN THE EXTENDED CORONA

The solar system in the ecliptic plane up to 1 AU and the positions of STEREO-A and -B spacecraft during the launch of the 2013 April 11 CME from the Sun are depicted in the plot of Figure 6. The eruption is seen on the solar disk from the Earth’s (SDO and LASCO) perspective and the CME was observed by SOHO/LASCO-C2 at 07:24 UT onwards as a full halo CME with a speed of the CME\(^3\) in the LASCO FOV, which was 861 km s\(^{-1}\) and was found to be decelerating. STEREO-A was located 133° west and STEREO-B was 141° east of the Earth, and so they could not observe the CME MFR during the initial times within the low corona. However, the separation angle between them (276°) makes it possible to observe the MFR as a bulk structure of the CME that emerged out of the occulter after 07:10 UT in the east limb of STEREO-

\(^{3}\) http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2013_04/
A and after 07:30 UT in the west limb of STEREO-B on April 11 (Figures 7 and 8, top panels). The MFR structure (as seen in classical three-part structured CME) could be identified as a dark cavity in the CME morphology in COR1-B. Since this CME is a halo event from the COR-A and LASCO views, its three-part structure could not be identified there. The new definitions suggest that the CMEs which travel beyond 10R_s are being supported by MFR topology and ruling out other possibilities of loops and jets (Vourlidas et al. 2013). Therefore, our description of the MFR topology to the observed morphology of the source region sigmoid (Sections 3–5) and the CME fits well with the observed properties in both the low and upper corona as well.

In order to reveal the underlying large-scale structure and orientation of the MFR by exploiting the plane of sky-projected images of the plasma structures, we need to determine its three-dimensional reconstruction using simultaneous imaging observations from multiple viewpoints. For this purpose, we employed simultaneous three-point, i.e., the SECCHI/COR-B, LASCO-C2/C3, and SECCHI/COR-A, white light observations of the CME, with a model called Graduated Cylindrical Shell (GCS; Thernisien et al. 2009). In this model, the large-scale structure of the MFR is approximated by two shapes: the conical legs and the curved (tubular) fronts, which is known as the “hollow croissant.” The involved inherent assumption in this model is that the magnetic orientation of an erupting CME MFR is constrained by the pre-eruptive magnetic configuration in the source AR, invoked after a study of many CMEs and their source region magnetic configurations (Cremades & Bothmer 2004). Before applying this model, a suitable background image was subtracted from a sequence of processed total brightness images.

Figures 7 and 8 (bottom panels) show the difference images of the CME at 07:30–07:24 UT [COR1-A, C2, and COR1-B] and 10:54–10:24 UT [COR2-A, C3, and COR2-B] on April 11, respectively. These panels are overlaid with a wireframe (green) of the MFR retrieved from an approximated fit of the GCS model. While fitting the GCS model, we input the source location position (latitude of 9° north, longitude of 13° east), tilt-angle (γ = −45°) of magnetic polarity inversion line (see Figure 2), and vary the height-aspect ratio (κ, major and minor radius of the MFR), half-angle (α) until achieving the best visual fit to the observed Thomson-scattered bright emission of the CME. Table 2 summarizes these fitted parameters at four different epochs of the CME propagation in the inner corona. At all four time instants, a half-angle of 50° and an aspect ratio of 0.45 gives the best resemblance to the projected MFR on to the plane of the sky. We point out that the constant value of κ during the outward motion of MFR indicates its self-similar nature of expansion as observed for many CME events (Subramanian et al. 2014) in the inner corona. Given the radial positions at successive time instances, intermediate velocities and their average value can be estimated. Thus, calculated instantaneous velocities 967 km s^{-1} [07:30–08:24 UT], 644 km s^{-1} [08:24–09:54 UT], and 773 km s^{-1} [09:54–10:54 UT] arrive at an average value of 795 km s^{-1}. Note that the published average velocity in C2 FOV from the plane of sky observations is 860 km s^{-1}. From this analysis of Earthward-directed CME MFR, it is clear that the determination of the parameters defining the MFR orientation from three-point observations is somewhat a near approximation and is useful to reproduce oblique cases when the MFR is not an edge-on (limb) event. As MFRs rotate on their outward propagation (Lynch et al. 2009) due to their inherent twist, it is quite possible that this MFR tilt will be −55° within the COR2 FOV as this value also fits the observed morphology very well.

7. PROPAGATION OF THE CME MFR IN THE HELIOSPHERE

7.1. Kinematics from Stereoscopic and Single Spacecraft Reconstruction Methods

It has been shown that different parts (structures) of the CME propagate and reach the Earth in the same order as observed in remote observations (Byrne et al. 2010; Liu et al. 2010; Howard & DeForest 2012). We acknowledge the difficulty in tracking the MFR of a CME using running difference images from HI. However, tracking a density enhanced feature as the leading edge of the CME, which is solar wind or coronal plasma pile-up ahead of the MFR and identified as shock-sheath region in situ data, is conveniently possible (Davies et al. 2009; Möstl et al. 2010; Mishra & Srivastava 2013). Assuming that the 3D kinematics of CME leading edge will also mimic that of the associated MFR, we have estimated the 3D kinematics of the leading edge using COR2, HI1, and HI2 observations from STEREO (Figure 9). From them, timeelongation maps (J-map; Davies et al. 2009) are constructed as shown in Figure 10. Positive inclination bright curves in the J-maps indicate the motion of the CME features away from the Sun. Using these J-maps, we tracked the bright leading front manually and derived their elongation time profiles (dashed red line).
The three most widely used stereoscopic reconstruction methods to estimate the kinematics of CMEs using SECCHI/HI observations are the Geometric Triangulation (GT; Liu et al. 2010) method, the Tangent to a Sphere (TAS; Lugaz et al. 2010) method, and the stereoscopic self-similar expansion (SSSE; Davies et al. 2013) method. These methods differ by assuming a different geometry for the CME. Davies et al. (2013) showed that the GT and TAS methods are special cases of the SSSE method corresponding to the cross-sectional angular half-width ($\lambda$) of the CME as $0^\circ$ and $90^\circ$, respectively. We therefore implemented the SSSE method to estimate the kinematics for the present case.

Using the elongation measurements (Figure 10) and the position of STEREO spacecraft, the estimated kinematics from the SSSE method for different values of $\lambda$ is shown in Figure 11. The plots for $\lambda = 0^\circ$, $30^\circ$, $60^\circ$ are shown until the CME reaches the L1 location, i.e., approx. $214R_\odot$ from the Sun. This is done to examine the role of the cross-sectional angular extent of the CME in estimating the kinematics. The estimated kinematics with $\lambda$ equal to $90^\circ$ is shown for relatively larger distances. It is evident that the estimated kinematics differs for different $\lambda$. It is to be noted that although distances and speeds derived from these methods vary significantly, the estimates of the direction and its trend from these methods are within $10^\circ$. Estimates of the direction from all methods suggest that the CME is propagating toward the east of the Sun–Earth line in the ecliptic plane. This is consistent with the solar source location of the CME and the estimated direction in the COR FOV from the GCS model.

We admit that there are several sources of errors (geometry, Thomson scattering, the optically thin nature of CMEs, the breakdown of assumptions considered in the methods itself) in implementing these methods and quantification of such errors is extremely difficult. However, to examine the effect of uncertainties in the estimated kinematics, we considered an error of 5 pixels in the measurements of the elongation angle. Such an error corresponds to uncertainties of $0.02^\circ$, $0.1^\circ$, and $0.35^\circ$ in the derived elongation angles in COR2, HI1, and HI2 FOV, respectively. Corresponding to these elongation uncertainties, the calculated error for the SSSE (with $\lambda = 0$) method maximally reaches up to $0.5R_\odot$ in distance, less than few degrees in direction and a few tens of km s$^{-1}$ for speed. These errors certainly seem to be small, but of course they do not reflect the total error in derived kinematics. Further study is required to quantify the actual errors because of several invalid idealistic assumptions in the methods.

Also, at higher elongation (greater than approx. $40R_\odot$), larger variations in the estimated kinematics from the SSSE method for different $\lambda$ are noted. From Figure 11, it is clear that the estimated distance from the GT method increased around 18:00 UT on April 11 at $90R_\odot$ from the Sun. Such an unphysically fast increase in distance and speed is meaningless due to the absence of forces capable of accounting for this acceleration at distances farther from the Sun (Cargill 2004; Vršnak et al. 2010). This is more likely because of improper
use of the SSSE with \( \lambda \) equal to 0° (i.e., GT) method, especially for this CME which is propagating away from the observer. This late acceleration is significantly reduced (still unphysical) if a higher value of \( \lambda \) is considered. The SSSE with \( \lambda \) equal to 90° (i.e., TAS) method gives the lowest limit of the estimated distance and speed values. The kinematics from the TAS method is calculated up to \( R_{\odot}^{365} \), the third heliopause.

The aforementioned facts highlight that the assumptions made in the GT method are not valid for a CME propagating away from the observer. Also, the spherical front approximation in the SSSE method with \( \lambda \) equal to a nonzero value becomes worse due to the flattening of the CME front on its interaction with the solar wind. These limitations start to play a crucial role much closer to the Sun for a far-sided CME than for front-sided CME (Liu et al. 2013). However, the distance beyond which these effects are crucial depends on the direction of the propagation of the CME and its size. We note that for a CME propagating at a larger angle from the Sun-

| Time (UT), Apr 11 | \( \kappa \) | \( \alpha \) (deg) | Height (\( R_{\odot} \)) |
|------------------|-------|-------------|-------------------|
| 07:30            | 0.45  | 50          | 4.0               |
| 08:24            | 0.45  | 50          | 8.5               |
| 09:54            | 0.45  | 50          | 13.5              |
| 10:54            | 0.45  | 50          | 17.5              |

![Figure 8](https://example.com/figure8.png)

**Figure 8.** Top panels: CME morphology observed from COR2-A, C3, and COR2-B, respectively, at 10:54 UT on 2013 April 11. Bottom panels: Overplot of the best-fitted wireframe of the MFR in the GCS model. Note this halo-CME heads toward Earth in C3, whereas it directs away from COR-A on the far side. Note that the GCS parameters \( \gamma = -45^\circ \), \( \alpha = 50^\circ \), \( \kappa = 0.45 \), and \( h = 17.5R_{\odot} \) reproduce this CME morphology.

observer line, its kinematics depend more on the chosen value of \( \lambda \). This is because the flanks (not nose) for such CMEs are always observed from the observer and even a little change in its radius of curvature leads to huge differences in the estimated kinematics from the SSSE method. It is noted that if the direction of the propagation of a CME from Sun-observer line becomes more than 90°, an unphysical acceleration will be estimated from the SSSE methods irrespective of chosen \( \lambda \) value. However, such an acceleration is reduced with a higher value of \( \lambda \) and gives more accurate kinematics.

To assess the relative performance, we also applied single-spacecraft reconstruction methods on STEREO-A and -B observations. We employed the Fixed-Phi (FP: Kahler & Webb 2007), Harmonic Mean (HM: Lugaz et al. 2009), Self-Similar Expansion (SSE: Davies et al. 2012) methods on the derived time-elongation variations of the CME (Figure 10). These methods essentially convert the elongation into distance from the Sun assuming a fixed direction (longitude, here 13° east) of the CME propagation as an input.

On applying the above methods on the STEREO-A and -B observations, we noticed that estimated kinematics also largely overestimates the speed (approx. 900–1200 km s\(^{-1}\) even beyond 100\(R_{\odot}\)) of the CME and the method becomes completely unreliable once the CME reaches higher elongations. The direction of the propagation of CMEs is 146° and 128° away from the line connecting the Sun with the S-TEREO-A and -B spacecraft, respectively. As the CME propagating in eastward is little closer to 90° from the
STEREO-B spacecraft, the derived kinematics and arrival time from this spacecraft are more accurate than using STEREO-A observations. Among all the three single-spacecraft methods, the most inaccurate results are obtained from the FP method and the less inaccurate results are from the HM method. This probably confirms the assumption that the larger structure of the CME is somewhat suitable for estimating the time varying profile of the CME kinematics. However, the failure of these single-spacecraft methods at higher elongation could be due to real deflection or artificial deflection because of the expansion or/and due to changes in the approximated idealized structure (Wood et al. 2010; Howard 2011; Mishra et al. 2014).

We further applied the fitting version of the three single-spacecraft reconstruction methods, namely Fixed-Phi Fitting (FPF: Sheeley et al. 2008), Harmonic Mean Fitting (HMF: Möstl et al. 2011), and Self-Similar Expansion Fitting (SSEF: Davies et al. 2012). Noting the expressions for the elongation as a function of speed and direction from the earlier FP, HM, and SSE methods, these methods fit the observed elongation time profile of the CME to an analytical function. From the FPF method on STEREO-A, we found that CME speed to be 654 km s$^{-1}$, its propagation direction as 99$^\circ$ from the S-STEREO-A spacecraft, and its launch time at April 11 05:05. Similarly, we also applied the HMF and SSEF methods (with $\lambda = 50^\circ$) and obtained the speed, propagation direction, and launch time of the CME. The results obtained for STEREO-A and B are shown in Figures 12 and 13, respectively, and summarized in Table 3. In these figures, the results for SSEF, which falls between the FPF and HMF methods, are not plotted to avoid cluttering.

Moreover, we have also analyzed the in situ observations of this CME obtained from the WIND spacecraft (Figure 14). The actual arrival time of the CME is marked by the arrival of a shock at 22:50 UT on April 13, which is followed by a prolonged (18 hr) sheath region. This sheath region is followed by an MC from 17:35 UT on April 14, whose signatures are indicated by the rotation of the magnetic field, an increase in the magnetic field strength to 14 nT, and a decrease in the temperature (of the order of 10$^4$ K). The duration of this MC traversal is approximately 25 hr at a speed of approximately
higher value of $f_i$ leading to large errors due to overestimated speed values. In light of these findings, it appears that in such a case, SSSE methods with a small elongation from the Sun may be because of inaccurate propagation angle and therefore they are unable to incorporate the real deceleration due to acting drag forces on the CME. This limitation of these methods is most obvious for CMEs propagating largely away from the Sun-spacecraft line. If we bear the uncertainties with the direction of the propagation of the CMEs, then the FPF method does a good job of estimating the arrival time of the CME at L1 point. We infer that in the FPF method the two sources of errors arising from not taking the geometry of the CME and physical deceleration into account actually cancel each other. However, any such physical deceleration is significantly counted in terms of geometrical (i.e., apparent) deceleration if the SSEF and HMF methods are used. The analysis of this event could help us to realize the

![Figure 10. Time-elongation maps (J-map) in the ecliptic plane for spacecraft A (top) and B (bottom) on STEREO using the running difference images of COR2, H11, and H12. The tracks of the 2013 April 11 CME are indicated with a red curve.](image)

**Figure 10.** Time-elongation maps (J-map) in the ecliptic plane for spacecraft A (top) and B (bottom) on STEREO using the running difference images of COR2, H11, and H12. The tracks of the 2013 April 11 CME are indicated with a red curve.

450 km s$^{-1}$, suggesting its width as approximately 0.27 AU, which is the average size of MCs as found by previous studies (Liu et al. 2005, 2006, 2010). The arrival of the shock (jump in density, temperature, and speed) structure ahead of the CME is expected to match the estimated arrival of the tracked density enhanced feature in the heliosphere using the J-maps as shown in Figure 10. Therefore, for a quantitative analysis, we compared the estimated arrival time by various reconstruction methods to that of in situ shock arrival and listed the errors in Table 3.

The errors in the estimated arrival time from the SSSE method with $\lambda$ equal to 0°, 30°, 60°, and 90° are earlier than the actual time by 46, 31, 26, and 21.5 hr, respectively. This shows that the estimates of the arrival time from HI observations have systematic fluctuations due to numerical differentiation and do not represent the real effect on the CME. It highlights the propagation of error into the kinematics due to even marginal uncertain tracking of the CME. Such a procedure for estimating the speed has the potential to reveal crucial short time variations in speed. However, the smoothed speed obtained by fitting the estimated distance–time curve into a polynomial may hide the short time variations in the CME speed.

![Figure 11.](image)

**Figure 11.** From top to bottom, the panels show the distance, propagation direction, and speed, respectively, of the 2013 April 11 CME MFR. The kinematics shown with red, blue, green, and black are derived from the SSSE method with $\lambda$ equal to 0°, 30°, 60°, and 90°, respectively. The estimated speed has systematic fluctuations due to numerical differentiation and do not represent the real effect on the CME. It highlights the propagation of error into the kinematics due to even marginal uncertain tracking of the CME. Such a procedure for estimating the speed has the potential to reveal crucial short time variations in speed. However, the smoothed speed obtained by fitting the estimated distance–time curve into a polynomial may hide the short time variations in the CME speed.

We noted that the HMF and SSEF methods estimate the propagation speed of the CME apex, which is not exactly toward the Earth, and therefore we have applied geometrical correction (Möstl & Davies 2013) to estimate its speed in an off-apex direction. This geometrically corrected speed, which is less than its speed derived in the apex direction, is used to obtain the estimated arrival time of the CME at L1 point.

From Table 3 it is obvious that among all the single-spacecraft reconstruction methods, the most accurate estimation of the CME arrival time (within an error of 3–8 hr) is obtained by the FPF method and the less accurate estimation by the HMF method. However, if we believe the direction of propagation of CME estimated from GCS model as accurate, then the estimation of the direction from the FPF methods is erroneous in agreement with Lugaz (2010). We find that even the fitting methods overestimate the speed of the CME. In principle, these fitting methods always overestimate the speed of the fast CME as they estimate a constant speed for the CME and therefore they are unable to incorporate the real deceleration.
potential differences in the results because of different fitting methods.

7.2. The CME Trajectory Reconstructed with the Drag-based Model

Despite using the SSSE method with $\lambda$ equal to 90$^\circ$, a rise in the CME speed around 14:00 UT on 2013 April 12 at a distance of 160$R_\odot$ is noticed. This large increase is unphysical for the reasons mentioned earlier and also due to the limitations of the SSSE method described in Mishra & Srivastava (2014). Moreover, the average in situ measured speed of the CME is around 450 km s$^{-1}$, whereas each method (even single-spacecraft-based) applied in our study overestimates the speed of the tracked feature of the CME and is why these methods estimate the arrival well before the in situ arrival. Therefore, beyond a certain radial distance from the Sun over which the CME is expected to maintain its deceleration, we have applied the DBM (Vršnak et al. 2013) to estimate the arrival time and speed of the CME at L1. The model is based on the hypothesis that beyond a certain distance, the CME dynamics become governed solely by the interaction of the CME and the ambient solar wind via aerodynamic drag (Cargill 2004; Vršnak et al. 2010). This assumption relies on the fact that in interplanetary space fast CMEs decelerate, and slow ones accelerate, showing a tendency to have their velocity trend toward that of the ambient solar wind. CMEs fulfill this assumption generally at heliocentric distances around or beyond 20$R_\odot$ (Vršnak et al. 2004). In the DBM model, the solution (position $r(t)$ and velocity $v(t)$) to the equation of motion describing the dynamics of the CMEs under the assumption of constant solar wind speed ($w$) and drag parameter ($\gamma$) is given by (Cargill 2004; Vršnak et al. 2013).

\[
r(t) = \frac{1}{\gamma} \ln\left[1 + \gamma (v_0 - w)t\right] + wt + r_0 \tag{3}
\]

\[
v(t) = \frac{v_0 - w}{1 + \gamma (v_0 - w)t} + w \tag{4}
\]

where $r_0$ and $v_0$ are initial heliocentric distance and speed of the CME.

Based on earlier works (Lepping et al. 1990; Howard & DeForest 2012), we assume that the MFR corresponds to the MC in situ observations and therefore it is logical to compare the actual arrival of the MC (here April 14, 17:35 UT) with that deduced from the propagation of the MFR in COR images. As $w$ and $\gamma$ are unknown under which conditions the CME is propagating (see Equation (3)), using the GCS kinematics as input to DBM, we performed a parametric analysis to obtain their approximate constrained values.

From the GCS fitting shown in Table 2, we constructed the radial distance profile by including more points. We fit that profile to a second order polynomial and then derived the velocity profile by invoking a smooth cubic spline interpolation procedure. This results in an expected deceleration of the CME in its outward propagation from 4$R_\odot$ onward. From the heliocentric distance of 17.5$R_\odot$ at the time instance 10:54 UT, we find that the CME is moving at a speed of 650 km s$^{-1}$. We
CME trajectory (Equations (3) and (4)) for its initial take off position and speed obtained from the GCS fit. As can be noted from this plot, the arrival times differed only by 5 hr about the mean value curve of \( w = 375 \text{ km s}^{-1} \). Also, the transit velocities vary from the mean value of \( 428 \text{ km s}^{-1} \) by only \( 24 \text{ km s}^{-1} \). This parametric analysis constructs the CME kinematics reasonably well, once we admit significant uncertainties in the CME takeoff position and speed.

7.3. Orientation of the Magnetic Field in MC of MFR

The source AR twist signatures are also explored in in situ observations of MC. When a CME reaches Earth, the magnetic field strength associated with the MC is stronger than the ambient field. Depending on the orientation of the MFR, the components of the MC magnetic field vary in time. We plotted in Figure 16 the observations of magnetic field components by the WIND instrument situated near the Lagrange point of Earth. These are one-minute averages and are in the Geocentric Solar Ecliptic (GSE) coordinate system, where the X-axis points from the Earth toward the Sun. Y is in the ecliptic plane but negative in the direction of planetary motion, and Z is parallel to the ecliptic north pole. Before the MC arrival, the field components exhibit rapid fluctuations due to shock and sheath regions. When the MC passes, the magnetic field components show systematic variation indicating strong magnetic field associated with MFR. The \( B_x \) and \( B_z \) components remain positive, while the \( B_y \) component changes sign from positive to negative around the mid-time (around 07:00 UT on April 15) of the MC passage. Based on this information and the nature of the twist in the source AR, we interpreted the possible orientation of the MFR up to L1 (Burlaga 1988; Yurchyshyn et al. 2001).

In Figure 17, we schematically sketched the Sun–Earth connections by the MFR in the XZ plane of the GSE system. In this figure, the axis of the MFR is approximately in the meridian plane whereas the MFR has an approximately \(-45^\circ \) tilt angle in the source AR. We point that there is now substantial observational evidence for the rotation of MFRs during their dynamic evolution and propagation (Green et al. 2007). Our schematic, however, is motivated by the observations of MFR rotation by about \( 45^\circ \) depending on its magnetic chirality (Lynch et al. 2009). In our case, although the tilt can be up to \(-55^\circ \) in the COR FOV, it can even smoothly vary up to \(-90^\circ \) tending toward the meridian plane. In a majority of cases (64%), CMEs in the COR FOV do have their orientation angles that differ within \( \pm 45^\circ \) with their interplanetary counterparts (Yurchyshyn et al. 2007).

The axial field is northward-directed (Ecliptic North) contributing to the \( B_z \) component, which is positive. In this predicted orientation, the MFR cuts the XY-plane in a circle having azimuthal field information and magnetic helicity (handedness) signatures of the MC. When the MC passes, different regions of this cross section encounter the spacecraft at different time phases (say t1, t2, t3 sequentially, here t2 is 07:00 UT on April 15). The projection of the azimuthal field on the y-axis at those time instances explains the sign and magnitude of the observed \( B_z \) component. We can suitably fix the spacecraft position on the y-axis depending on the observed sign of the \( B_z \) component, which is positive here. Obviously, the handedness of this azimuthal field should be negative (left) in order to match the observed \( B_z \) component variation from positive to negative, which is consistent with the
source AR signatures of the inverse S sigmoidal structure and
the negative value of $a$. This event is similar to the one observed on 2000 February 21 (Yurchyshyn et al. 2001) with right-hand twist, where the $B_z$ component of the MC changes sign from negative to positive value. It is possible to explore the twist quantitatively by reconstructing the magnetic field components in the MC cross section (Hu et al. 2014), however, those details are beyond the focus of this paper and require a separate study.

**8. SUMMARY**

CME eruptions from source ARs with soft X-ray sigmoids or Hα filaments are modeled as manifestations of MFRs to describe many observational features. In the context of Sun–Earth connections of an eruption event on 2013 April 11, we investigate the formation/development scenario of a sigmoid/MFR, the initiation of the rise motion, and its propagation through space.
toward Earth. From EUV observations of the AIA, the pre-
ruptive source AR consisted of a filament channel stacked
over by a faintly visible inverse sigmoidal structure for three
days. In view of the description of this flux system as an MFR
of field lines wound about some common axis, the morpho-
logical study of its evolution during a 48 hr period implies a
scenario of augmenting MFR. This augmentation is evidently
found to occur by the reconnection of inclined loops lying
beside the filament. Under the slow flux motions, both the
transformation of the distant OL toward sheared arcade (stage
1) and their reconnection (stage 2) at the middle of the sigmoid
are the suggested scenarios involved in the development of this
sigmoidal MFR.

The HMI magnetic field measurements in the source AR
support the EUV observations, showing monotonic decreasing
net flux for the last two days. The net flux from the rope leg and
the entire AR, according to MFR insertion models (Bobra
et al. 2008; Savcheva & van Ballegooijen 2009), implies a
marginal stability of the system of axial flux confined by the
overlying poloidal flux. The average twist of the flux system in
the AR also suggests a rapid build up of the MFR structure past
7 hr to the onset of the eruption. It also suggests the availability
of critical twist (VZ14) in order to initiate rise motion of the
MFR. Therefore, this study of the EUV and magnetic fields
suggests that the developed MFR system is initiated to upward
motion by kink instability to reach to a height (31 Mm) from
which the steep gradients of the horizontal field (torus
instability criteria (Török & Kliem 2005) drives its further
outward motion in the outer corona.

While expanding in the extended corona (after 07:10 UT,
2–30R\(_\odot\)), the CME morphology captured from the COR1,
COR2, and LASCO views visually fits with a parametrized
MFR orientation, which aligns with the orientation of the
magnetic neutral line in the source AR. Tilt angle is a crucial
parameter in determining the orientation of the MFR. MFRs by
virtue of inherent twist are shown to rotate up to 50° while
propagating (2–4R\(_\odot\)) in the low corona (Lynch et al. 2009).
This backsided halo CME did not allow us to detect the exact
extent of possible MFR rotation. However, a tilt angle of ~45°
projects the MFR onto the plane of sky to sufficiently map the
white light features of this halo CME event. An unchanged
aspect ratio value (ratio of minor to major radius of
MFR = 0.45) at successive stages of this CME MFR indicates
its self-similar nature of expansion. Tracking methods found
that the CME is propagating about 10° to the east of the Sun–
Earth line. This is consistent with the solar source location of
the CME and the estimated direction in the COR FOV from the
GCS model.

Although source AR magnetic configuration defines the
MFR orientation, due to the bulk in size combined with
projection effects, the exact orientation of the MFR in inter-
planetary space is difficult to predict within 45° (Yurchyshyn
et al. 2007). The predicted MFR orientation (MFR axis is in a
vertical plane to ecliptic; see Figure 17) identifies the source AR
twist signatures, which is left-handed, in the in situ
magnetic field observations of the MC. This predicted
orientation based on in situ observations, if correct, alterna-
tively suggests a possible rotation (clockwise as seen in the line
of sight direction, to align with the meridian plane) of the MFR
apex up to 45° while traveling from the Sun to the near-Earth
environment. It is worth noting that the B\(_z\) component of this
MC is northward, and consequently no geomagnetic activity
was associated with this CME.

Our analysis underlines the overestimation of the speed from
all the stereoscopic methods applied on the 2013 April 11
CME. Therefore, for the selected CME, when the STEREO
is behind the Sun, tracking of CME shock, leading edge, and flux
ropes, and predicting their arrival time at 1 AU is challenging.
Further, for the position of STEREO between 2011 February
and 2019 June, any Earth-directed CME will be moving away
from the STEREO spacecraft, and hence the estimation of
kinematics and arrival time of CME during this time is expected
to result in large errors.

Stereoscopic reconstruction methods lead to worse results
than single-spacecraft reconstruction methods. We note that
fixed-phi fitting method seems to perform best among all the
reconstruction methods used in our study. As the physical
deceleration of the CME is translated as geometrical deceler-
ation in fitting methods, the SSEF and the HMF methods
seem to work worse than the FPF method for this quickly
decelerating CME. Based on our analysis limited to a single
event, we suggest that the use of the FPF method should be
done for the practical purpose of arrival time prediction of such
a CME. However, in the absence of fitting methods, we must
use the reconstruction methods (i.e., TAS and HM) which
approximate the CME as a very wide structure (i.e., higher

Figure 17. Schematic of the MFR orientation in par with in situ magnetic field observations. Rotation of the observed B\(_z\) component is demonstrated by the azimuthal field and its handedness in the MC, which is shown by a cross section of the MFR in the XY-plane of the GSE coordinate system. Note that axial field contributes to the positive B\(_x\) component (northward-directed), consistent with in situ observations.
value of $\lambda$ for estimating the kinematics and arrival time of a CME moving at a higher angle from Sun-spacecraft line.

As almost all applied reconstruction methods failed to estimate accurate arrival time, alternatively, our study suggests that the estimated kinematics by the implementation of the GCS model on COR2 observations can preferably be used as inputs in the DBM (Vršnak et al. 2010) to reconstruct the CME trajectory and thereby estimate the arrival time. By a combination of parametric study and observations, the unknown parameters like solar wind speed and drag parameter can be constrained suitably to match the in situ arrival.

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