A STUDY OF A FAILED CORONAL MASS EJECTION CORE ASSOCIATED WITH AN ASYMMETRIC FILAMENT ERUPTION

NAVIN CHANDRA JOSHI1, ABHISHEK K. SRIVASTAVA1, BORIS FILIPPOV2, WAHAB UDDIN1, PRADEEP KAYSHAP1, AND RAMESH CHANDRA3

1 Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital-263 002, India; navin@aries.res.in, njoshi98@gmail.com, aks@aries.res.in
2 Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, Troitsk, Moscow, Russia
3 Department of Physics, D.S.B. Campus, Kumaun University, Nainital-263 002, Uttarakhand, India

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ABSTRACT

We present multi-wavelength observations of an asymmetric filament eruption and associated coronal mass ejection (CME) and coronal downflows on 2012 June 17 and 18 from 20:00–05:00 UT. We use SDO/AIA and STEREO-B/SECCHI observations to understand the filament eruption scenario and its kinematics, while LASCO C2 observations are analyzed to study the kinematics of the CME and associated downflows. SDO/AIA limb observations show that the filament exhibits a whipping-like asymmetric eruption. STEREO/EUVI disk observations reveal a two-ribbon flare underneath the southeastern part of the filament that most probably occurred due to reconnection processes in the coronal magnetic field in the wake of the filament eruption. The whipping-like filament eruption later produces a slow CME in which the leading edge and the core propagate, with an average speed of \(\approx \frac{540 \text{ km s}^{-1}}{R_{\odot}}\) and \(\approx \frac{126 \text{ km s}^{-1}}{R_{\odot}}\), respectively, as observed by the LASCO C2 coronagraph. The CME core formed by the eruptive flux rope shows outer coronal downflows with an average speed of \(\approx \frac{56 \text{ km s}^{-1}}{R_{\odot}}\) after reaching \(\approx \frac{4.33 R_{\odot}}{R_{\odot}}\). Initially, the core decelerates at \(\approx \frac{48 \text{ m s}^{-2}}{R_{\odot}}\) and then starts accelerating downward. We suggest a self-consistent model of a magnetic flux rope representing the magnetic structure of the CME core formed by an eruptive filament. This rope loses its previous stable equilibrium when it reaches a critical height. With some reasonable parameters, and inherent physical conditions, the model describes the non-radial ascending motion of the flux rope in the corona, its stopping at some height, and thereafter its downward motion. These results are in good agreement with observations.

Key words: magnetic fields – Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences

Online-only material: animations, color figures

1. INTRODUCTION

Filaments and prominences are composed of cool (10^4 K) and dense (10^9–10^11 cm\(^{-3}\)) plasma material embedded in the magnetic field of the ambient solar atmosphere (Mackay et al. 2010; Labrosse et al. 2010 and reference therein). These solar magnetic structures are the same intrinsically but appear different due to projection. Prominences, when observed on the solar disk, show bright filaments and are the same intrinsically but appear different due to projection. Prominences, when observed on the solar disk, are known as solar filaments and lie along the polarity inversion line (Durrant 2002; Filippov & Srivastava 2011). Filaments may remain in the quiescent state for several days over the solar disk, while some filaments may exhibit an eruptive nature. Filament eruption occurs mainly due to non-equilibrium between the upward magnetic pressure and the downward magnetic tension. Eruption may also arise from the tether cutting between magnetic flux ropes containing filaments and overlying arcades (Mackay et al. 2010). Filaments show different types of eruptions such as failed eruptions (Liu et al. 2009b), partial eruptions (Tripathi et al. 2009), and full eruptions (Schrijver et al. 2008; Chandra et al. 2010). Apart from these eruptions, filaments can also undergo asymmetric eruptions with one footpoint fixed in the photosphere (anchored leg) while the other shows dynamic motion (active leg) (Liu et al. 2009a; Yang et al. 2012). The eruption of a flux rope can be either partial or full, depending on the overlying magnetic field configuration. Recently, Kumar et al. (2011) observed a huge flux rope that failed in its eruption; these authors suggest that the overlying filament remnant and coronal magnetic field caused its suppression. It is widely reported in the literature that the emergence of new magnetic flux, the generation of the high critical twist, and low-lying atmospheric reconnections can generate eruptions and instabilities of flux ropes that may further lead to the outer coronal transients (Srivastava et al. 2010; Chandra et al. 2011; Yan et al. 2012; Zhang et al. 2012; Botha et al. 2012; Srivastava et al. 2013). However, it is also found that these conditions may only be necessary, but not sufficient, for solar eruptions. The configuration of the ambient magnetic field as well as its strength may also play a role in deciding the nature and morphology of the eruptions (Kumar et al. 2011 and references cited therein).

Eruptive filaments are closely associated with coronal mass ejections (CMEs). CMEs are the propulsion of large-scale plasma outflows and magnetic fields into the outer corona and interplanetary space (Joshi et al. 2013). In general, a CME has a three-part structure, i.e., a leading edge, a dark cavity, and a bright core associated with the eruptive filament (Riley et al. 2008 and references therein). CMEs produce outward movement in the corona; this movement may be either driven by magnetic pressure or by a shock in the background of the ambient solar wind (Filippov & Srivastava 2010). The less dense outer corona sometime shows downflows of the plasma blobs, CME cores, etc. Such downflows of the magneto-plasma are collectively termed “coronal inflows” or “coronal downflows.” Various kinds of inflows/downflows into the solar corona have been observed and analyzed, including prominence fallback (Tripathi et al. 2006b, 2007), downflow over the post flare arcades (Innes et al. 2003; McKenzie & Hudson 1999; McKenzie 2000; Asai et al. 2004), and inflow of small, faint plasma structures and blobs,
etc. (Wang et al. 1999, 2000; Wang & Sheeley 2002; Sheeley & Wang 2002).

Innes et al. (2003) have exclusively observed a series of dark and sunward moving plasma flows, which were observed and seen against the bright extreme ultraviolet (EUV) post flare loop arcades associated with the large eruptive flare on 1999 April 21. Asai et al. (2004) have investigated the down-flowing plasma motions above the flaring loops observed on 2002 July 23, and found that such dynamics may occur in the solar corona above the flaring region when the magnetic energy is released. In all these examples, reconnection is responsible for the downflows in the inner solar corona. In spite of such observed downflows in the inner corona, reconnection in the outer corona may also be responsible for downflows there. Wang et al. (1999) reported various small and fainter plasma flows moving through the corona, and found that these inward motions are the observational signature of the gradual closing-down of magnetic flux tubes dragged outward by the CMEs or other transient outflows. Wang et al. (2000) studied a variety of small-scale downflowing structures (e.g., plasma blobs) during high solar activity and interpreted these downflows as being due to magnetic reconnection between the closed and open field regions of the corona. Sheeley et al. (2001) reported that the inflow rate was dominated by transient bursts, which were correlated with the existence of non-polar coronal holes and other signatures of the solar non-axisymmetric open field structures. Wang & Sheeley (2002) and Sheeley & Wang (2002) identified faint, inward-moving features, e.g., collapsing loops, sinking plasma columns, falling plasma curtains, in and out pairs of oppositely directed plasma ejecta, and downflow of the core of CMEs at heliocentric distances from 2 to 6 Rs. These authors interpreted these structures as initiation stages of large-scale magnetic reconnection. Tripathi et al. (2006b, 2007) also reported coronal downflows during prominence eruption and associated CME on 2000 March 5, interpreting the origin of such downflows as being due to reconnection inside the bifurcating flux rope.

As discussed above, the CME core sometimes exhibits downfall depending on the local magnetic field and plasma configurations. The most probable reason for the core exhibiting downfall may be the pre-settings of the large-scale reconnection in the outer corona. The CME itself can also produce several changes in the outer coronal magnetic fields in the form of deflection of coronal streamers, kink propagation in coronal rays, etc. (Filippov & Srivastava 2010). Filippov & Srivastava (2010) analyzed the events of the interaction of CMEs with the coronal rays observed by SOHO/LASCO and interpreted these deflections as the influence of magnetic fields of moving flux ropes associated with CMEs on the remote coronal rays. In this paper, we report on a multi-wavelength investigation of asymmetric filament evolution and eruption, associated CME, coronal downflows, and their relationships using the observations from the Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA), the Solar Terrestrial Relations Observatory/Sun Earth Connection Coronal and Heliospheric Investigation (STEREO/SECCHI) and the Solar and Heliospheric Observatory/Large Angle and Spectrometric Coronagraph (SOHO/LASCO) C2 instruments on 2012 June 17 and 18 during 20:00–05:00 UT. The observational results are presented in Section 2. Physical scenarios of the observations are discussed in Section 3. Discussion and conclusions are outlined in the last section.

2. OBSERVATIONAL RESULTS

We use multi-wavelength and multi-instrument data from SDO/AIA (Lemen et al. 2012), STEREO-B/SECCHI (Wuelser et al. 2004), and the SOHO/LASCO C2 coronagraph (Brueckner et al. 1995) for this study. We use SDO/AIA 304 Å and 171 Å data to study the filament evolution and its kinematics as it provides a limb view for this event with fewer projection effects. SECCHI EUVI data (304 Å, 195 Å, and 171 Å) have been used to study the on-disk view of filament evolution in the particular eruptive region. We also use LASCO C2 data to study the CME kinematics and the downflows of its core in the outer solar corona.

Figure 1 shows the full disk images of the Sun in the STEREO/EUVI 171 Å and SDO/AIA 304 Å passbands. The boxes in these images show the location of the filament. Observations from both STEREO-B/SECCHI and SDO/AIA provide a unique opportunity to study filament eruption on the disk as well as on the limb. The filament is located on the solar disk on the southwestern side, as indicated by the box in the field of view of STEREO-B (Figure 1, left image). At the same time, SDO/AIA observes the filament on the southeastern limb of the Sun (Figure 1, right image). In the subsequent sections, we discuss the observations of the highly asymmetric filament eruption and the two-ribbon flare, as well as their association with the CME and the downflow of its core in the outer corona. Table 1 shows the timeline of the whole event starting from the filament eruption and ending with the downflows of the CME core in the outer corona.

2.1. STEREO-B/SECCHI and SDO/AIA Observations of the Asymmetric Filament Eruption and the Two-ribbon Flare

Figure 2 shows a sequence of selected EUV 304 Å images (T$_{eff}$ = 0.07 MK) of the filament evolution as observed by STEREO-B/SECCHI. A long dark filament is clearly seen in the southwest hemisphere over the solar disk (cf. snapshot at 20:26:36 UT). The leading edge (northwest part) of the eruptive filament is indicated by the white arrows. Thereafter, the whole filament exhibits a whipping-like asymmetric eruption. A two-ribbon flare was observed underneath the southern part of the former filament position. The flare was unclassified in the GOES X-ray fluxes because it occurred on the invisible side of the Sun. The two ribbons of the flare (indicated by R1 and R2 at the snapshot at 21:06:36 UT) are clearly visible. The flare occurred when the eruptive filament accelerated from slow speed to high speed (Figure 7). For a detailed discussion of the physical scenario, we refer the reader to Section 3.1. The flare ribbons separate from each other as the filament eruption progresses. The northwestern leg of the filament remains anchored to the Sun, while all the material in the filament channel first whipped and later erupted asymmetrically. Figure 3 shows a sequence of selected EUV 195 Å (T$_{eff}$ = 1.4 MK) images of the filament evolution as observed by STEREO-B/SECCHI. The dark filament is also observed over the disk in the southwest of the solar disk (see the snapshot at 20:50:51 UT). In the coronal images, the fine and brightened coronal magnetic flux tubes that cross the southern part of the filament are clearly visible. The overlying magnetic field lines are clearly visible in this wavelength, as indicated by the red arrows (cf. images at 21:00:51 and 21:05:52 UT in Figure 3). These arches may be part of a moderately active region lying on the eastern side of the filament (not shown here). The white arrows indicate the evolution of the leading edge (the northwest segment) of the filament in the corona. The two-ribbon flare, and asymmetric whipping-like eruption of the filament with its detached (southern) and anchored (northern) legs, are visible in the 21:20:51 UT snapshot.
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Figure 1. STEREO-B/SECCHI 171 Å (left) and SDO/AIA 304 Å (right) images showing the full disk of the Sun on 2012 June 17. The boxes show the location of the filament from two different angles.

(A color version of this figure is available in the online journal.)

Table 1: Timeline of the Event

| S. No. | Date (Time) | Observations |
|--------|-------------|--------------|
| 1.     | 2012 Jun 17 (before 20:30 UT) | Filament is observed on the Sun. |
| 2.     | 2012 Jun 17 (∼20:30−∼20:56 UT) | Slow rise of the filament with a speed around 3 km s⁻¹. |
| 3.     | 2012 Jun 17 (∼21:00−∼21:14 UT) | Fast rise of the filament with a speed around 205 km s⁻¹. |
| 4.     | 2012 Jun 17 (∼21:36 UT) | First appearance of the CME in the LASCO C2 field of view. |
| 5.     | 2012 Jun 17 (∼22:12 UT) | First appearance of the CME core in the LASCO C2 field of view. |
| 6.     | 2012 Jun 17 (∼22:36 UT) | Start time of the coronal ray deflection. |
| 7.     | 2012 Jun 17 (after ∼22:36 UT) | Maximum deflection time of the coronal ray. |
| 8.     | 2012 Jun 18 (after ∼00:48 UT) | Returning motion time of the coronal ray. |

Figures 4 and 5 show a sequence of images in the SDO/AIA 304 Å ($T_f = 0.05$ MK) and 171 Å ($T_f = 0.6$ MK) channels, respectively. These images display the evolution of the filament eruption. The whole filament is made up of several threads already visible on the southeast limb of the Sun on 2012 June 17. The white arrows indicate the leading edge of the eruptive filament. The observations show the asymmetric evolution and whipping of the filament (see animation related to Figure 4). The whipping motion of the flux rope took place between ∼21:04 and ∼21:10 UT. During the whipping motion, most of the filament plasma was channeled from the southern part to the northern part. The whipping and asymmetric eruption of the filament is indicated by the yellow arrow (cf. 21:10 UT snapshot in Figures 4 and 5). After the whipping motion, the filament erupted asymmetrically higher in the corona toward the northern side of the Sun. The post-flare loops in the southern side are visible during the decay phase of the flare (see the 22:10:08 UT snapshot in Figure 4 and the 23:00 UT snapshot in Figure 5). It is also interesting to note in the AIA 171 Å coronal image that the filament plasma shows some heating in the form of plasma brightening in the eruptive part. This observation may give a clue about the energy deposition and initiation of the whipping-like asymmetric eruption through the magnetic reconnection in its southern part. This observational scenario matches well with the on-disk scenario of this filament eruption as observed by STEREO. The schematic representation of the asymmetric whip-like filament eruption and its comparison with the SDO/AIA 304 Å image at 21:06:08 UT is shown in Figure 6. The upper panel of Figure 6 shows the SDO/AIA 304 Å image of the filament eruption at 21:06:08 UT. The arrows indicate the two legs of the filament. The filament image is rotated by 90 deg clockwise from its real position to compare with the schematic diagram. The bottom panel of Figure 6 shows the schematic of the whipping-like asymmetric filament eruption. The red line indicates the polarity inversion line.

Figure 7 shows the height–time plot of the filament using the SDO/AIA 304 Å image sequence. The filament shows a slow rise followed by a fast rising phase. The speed of the slow rise is around 3 km s⁻¹, while the fast rising phase has a speed of about ∼205 km s⁻¹. The filament rises slowly from 20:30 UT to 20:56 UT, and thereafter exhibits a fast rising phase from 21:00 UT to 21:14 UT. The whipping-like asymmetric eruption of the filament took place around its transition from the slow rise to the fast rise phase (Sterling & Moore 2005). After the whipping motion, the filament erupted with a high speed. The speed has been calculated from the linear fit to the height–time...
data. When we examine the composite image (Figure 8) of the SOHO/LASCO white light image on 2012 June 17 at 23:24 UT and the SDO/AIA 304 Å image at 21:15 UT (inside), we see an occurrence of a high degree of asymmetric filament eruption that later constitutes the CME core. The detailed outer coronal dynamics is described in the next subsection.

2.2. LASCO C2 Observations of the CME and Downflow of Its Core in the Outer Corona

The LASCO C2 coronagraph observed the CME associated with the asymmetrical eruptive filament on 2012 June 17 and 18 from 21:36 to 04:48 UT. It was a slow CME, which appeared from the east side of the coronagraph occulting disk. Figure 9 shows a sequence of the difference images, showing the CME and its core eruption. Thereafter, the CME core falls down, which initiates the outer coronal downflows (see animation related to Figure 9). The CME first appears in the LASCO C2 field of view at ≈21:36 UT on 2012 June 17. The red arrows in panels (a)–(c) of Figure 9 indicate the outward motion of the CME’s leading edge. The core of the CME, which is the filament flux rope, was initially observed in the LASCO C2 field of view at ≈22:12 UT. The position angle and the width of the CME were ≈90° and ≈125°, respectively.

Figure 10 shows the height–time plot of the CME leading edge and the CME core (Figure 10(a)), the derived velocity and acceleration profiles of the core with time (Figure 10(b)), as well as the same profiles with distance (Figure 10(c)). The solid black line shows a linear fit of the form $y(t) = a + bt$ to the measured height of the CME leading edge with respect to time. From the linear fit, the speed $(dy(t)/dt = b)$ of the
Figure 3. STEREO-B/SECCHI 195 Å images showing the activation of the filament. The white arrows represent the eruption of the filament. Downward red arrows indicate the overlaying magnetic field arches above the southern part of the filament. The yellow arrow indicates the interaction of the filament with the overlaying magnetic field. Post-flare loops (PFLs) are shown in the bottom panel. (A color version of this figure is available in the online journal.)
Figure 4. SDO/AIA 304 Å images showing the evolution and eruption of the filament. White arrows indicate the erupting leading edge of the filament. The bottom right image shows the post-flare loops (PFLs).

(An animation and color version of this figure are available in the online journal.)
Figure 5. SDO/AIA 171 Å images showing the evolution and eruption of the filament. White arrows represent the evolution of the filament leading edge. Post-flare loops (PFLs) on the southern part of the filament are clearly visible in the bottom right image.

(A color version of this figure is available in the online journal.)
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Figure 6. Upper panel: SDO/AIA 304 Å image of the filament eruption at 21:06:08 UT. The arrows indicate the two legs of the filament. The filament image is rotated by 90° clockwise from its real position to compare with the schematic diagram. Bottom panel: schematic diagram of the whipping-like asymmetric filament eruption. The red line indicates the polarity inversion line. (A color version of this figure is available in the online journal.)

Figure 7. Height–time plot of the filament leading edge (indicated by the white arrows in Figure 4) measured using the SDO/AIA 304 Å time-series. (A color version of this figure is available in the online journal.)

CME leading edge is estimated to be ≈540 km s⁻¹. The dotted blue line shows the height of the CME core with respect to time. From the linear fit to the upward motion of CME core, we obtain its average velocity as ≈126 km s⁻¹. Using the same method, we estimate an average velocity of ≈56 km s⁻¹ during the core downflow. In order to determine the velocity and acceleration at each point of the parabolic path of the CME core, we perform a third order fit. The blue dotted line over these points shows the third order fit of the form \( y(t) = a + bt + ct^2 + dt^3 \). The velocity and acceleration profiles are derived by differentiating the above equation at each point along the height–time profile (Figure 10(b)). It is clear from Figure 10(b) that the velocity of the CME core attains a zero value at ≈00:48 UT on 2012 June 18 when it reaches the maximum height. The CME core shows continuous deceleration. The deceleration rate changes from its initial value of −48 m s⁻² to −19 m s⁻² at its maximum height. Thereafter, it starts downflowing with acceleration rates ranging from −21 m s⁻² at 00:48 UT to −14 m s⁻² at 03:48 UT (see the velocity and acceleration profiles in Figure 10(b)). We also plot the velocity and acceleration profiles of the CME core with respect to radial distance. The initial velocity at ≈2.54 \( R_\odot \) is ≈312 km s⁻¹, which continuously decreases with height and becomes zero at ≈4.33 \( R_\odot \) (see Figure 10(c)). After the start of the downflow at ≈4.33 \( R_\odot \), its initial speed is around ≈10 km s⁻¹. The downflow later reaches speeds up to ≈30 km s⁻¹ at 3.56 \( R_\odot \). The initial deceleration was ≈48 m s⁻² at a height of ≈2.54 \( R_\odot \). At 4.33 \( R_\odot \), the deceleration was 21 m s⁻². During the fall of the core from this height, it reaches zero deceleration and then tends toward positive values. The value of deceleration/acceleration during the motion of the core did not match the local gravitational acceleration \( GM_\odot/r^2 \sim 68(2R_\odot/r)^2 \) m s⁻² (Wang & Sheeley 2002; see Figure 10(c)). This evidently shows that gravity is not the dominant force controlling the observed downward motion. We also observe the interaction of the CME with the coronal ray
Figure 9. Time sequence of LASCO C2 images showing the CME eruption ((a)–(c)) and falling down of the CME core material (e–l) on 2012 June 17 and 18. Red arrows indicate the evolution of the CME leading edge (LE). White arrows indicate the down flow (DF) of the CME core. Yellow arrows indicate the coronal ray deflection. These difference images were taken from the SOHO LASCO CME catalog (http://cdaw.gsfc.nasa.gov/CMElist/).

(An animation and color version of this figure are available in the online journal.)

in the northward direction of the outward moving core. The red curve in Figure 10(a) shows the coronal ray deflection from its mean position at a height of $\approx 3.1 \ R_\odot$. The deflection started around 22:12 UT on 2012 June 17 soon after the appearance of the CME core in the LASCO field of view and continued with the upward motion of the CME. The coronal ray is deflected a maximum of $3.2 \times 10^5$ km at $\approx 22:36$ UT in the north and then returns back to its mean position.
3. A PHYSICAL SCENARIO OF THE OBSERVED DYNAMICS

The observations of the asymmetric filament eruption, the formation of the two-ribbon flare, and their relationship with the CME and the outer coronal downflows are discussed in detail in the previous section. In this section, we describe possible physical scenarios and theoretical interpretations for the observed coronal dynamics.

3.1. Asymmetric Filament Eruption and the Two-ribbon Flare

Asymmetric flux-rope eruptions have been studied by various authors (Tripathi et al. 2006a; Liu et al. 2009b and references therein). We observed the whipping-like asymmetric filament eruption. The whipping-like asymmetric filament eruption is characterized by an active leg whipping upward and hard X-ray sources shifting toward the end of the anchored leg (Liu et al. 2009b). We do not have X-ray observations in our case. However, we could not find any evidence of the transport of flare ribbon brightening (low energy counterparts) toward the anchored leg of the filament. This is a somewhat unique situation differing from the observations of Liu et al. (2009b). In this observational baseline, it is clear that the northern part of the filament has a comparatively homogeneous overlying corona, while its southern part experiences a crossed overlay of thin and brightened flux tubes. In the southeast direction, there is a moderately active region whose arches crossed above the southward part of the filament and suppressed it initially. During the whipping motion of the southern part of the filament, these overlaying magnetic flux tubes probably allowed only the formation of a compact two-ribbon flare beneath the eruptive part of the filament. This flare brightness does not spread much along the neutral line as in the case of large flares (Benz 2008).
The filament erupts asymmetrically and the two-ribbon flare occurs beneath it. The flare may be triggered due to reconnection in the vertical current sheet between the surrounding coronal fields in the wake of the eruptive filament (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976; Shibata 1999 and references cited therein). As reconnection progresses per these canonical models, formation of post-flare loops, and the propagation of the brightening along the ribbons (as well as their separation), is evident in the lower part of the solar atmosphere.

3.2. Coronal Downflows due to the Failed Flux-rope Eruption

The eruptive filament forms the core of the CME. The degree of asymmetry is large in this eruption. It is clear from Figure 8 that in spite of radial motion, the filament expands in the outer corona (CME core) at almost an angle of \( \approx 50^\circ \). The filament constitutes the outer coronal dynamics in form of a downflow. Later on, the core shows the downflow of its plasma. The physical reason in this observational baseline may be twofold, e.g., (1) the self-consistent equilibrium of the flux rope below a critical height, during its subsequent eruption in the form of whipping motion and the formation of the CME’s core (Filippov et al. 2001, 2002). (2) The interaction of the moving CME core with the ambient medium reduces its momentum (Wang & Sheeley 2002). Before the start of downflow, the CME core causes the deflection of a coronal ray in the northward direction in the LASCO C2 field-of-view (cf. Figure 9). The deflection measurement has been carried out at a height of around \( \approx 3.1 \, R_\odot \). The ray started deflecting around 22:12 UT and reached a maximum displacement of \( 3.2 \times 10^5 \, \text{km} \) at \( \approx 22:36 \) UT on 2012 June 17 (cf. Figure 10(a)). This was the period when the CME core was trying to move ahead with the average velocity of \( \approx 126 \, \text{km s}^{-1} \) (cf. Figure 10(b)). The coronal ray deflection and its restoring are most likely caused by the expansion of the CME-core magnetic field and its interaction with the radial field of the coronal ray (Filippov & Srivastava 2010). However, during the coronal ray restoring motion, the downflow of the CME core started when the coronal ray moved almost 50% toward its equilibrium position on \( \approx 01:00 \) at 2012 June 18 (see Figures 9 and 10(a)). This was the time when the CME core started down flowing with an average speed of around 56 km s\(^{-1}\). Both the opposite southward motions of the coronal ray (in projection) and the coronal downflow progressed simultaneously and finally ended at \( \approx 03:48 \) UT on 2012 June 18. This interaction and co-temporal dynamics of the coronal ray and coronal downflow is, to the best of our knowledge, observed here for the first time. However, the one-to-one relation between the restoration of the coronal ray and the downflow is not established here as the downflow starts more than two hours later after the initial restoring motion of the deflected coronal ray toward its equilibrium position. Therefore, coronal ray deflection may only be the consequence of the upward moving CME core; however, it does not start the downflow of the CME core.

The most likely cause may be the self-consistent evolution of the flux rope itself, which forms the CME core. We compare the observed evolution of the eruptive filament and the CME with the model developed by Filippov et al. (2001, 2002) for the non-radial flux-rope motion. This model was applied to the event on 1997 December 14 whose initial phase was very similar to the eruption studied in this paper. In the December 14 event, the filament erupted from a middle latitude in the southern hemisphere, while the CME was observed close to the equatorial plane. In this case, the CME core propagates even at some angle to the north of the equatorial plane (cf. Figure 8).

In both cases, the filaments propagated significant distances in latitude. However, on 1997 December 14, the true fast CME was observed, while in this case, on 2012 June 17 and 18, the CME core is stopped at some height and then falls down.

In the axially symmetric model of Filippov et al. (2001, 2002), the flux rope was represented by a thin current-carrying plasma ring (torus) with a total electric current \( I \) located above the photosphere along a heliographic parallel. A similar model for a ring located in the equatorial plane was analyzed by Lin et al. (1998). After integrating over the torus volume, we can obtain the equation of motion of the torus as a whole, as well as an equation describing the variation in its inner radius. In cylindrical coordinates \((\rho, \varphi, z)\) with their origin at the solar center and the \( z \)-axis directed along the rotational axis, the equations of motion for a toroidal segment with unit length take the form

\[
\frac{d^2 \rho}{dt^2} = \frac{I}{c} (B^{(ex)}_{\rho} + B^{(m)}_{\rho} + B^{(i)}_{\rho}) - mg R^2 \frac{\rho}{(\rho^2 + z^2)^{3/2}} - kv_{\rho},
\]

\[
\frac{d^2 z}{dt^2} = \frac{I}{c} (B^{(ex)}_{z} + B^{(m)}_{z}) - mg R^2 \frac{z}{(\rho^2 + z^2)^{3/2}} - kv_{z},
\]

where \( m \) is the mass of the filament per unit length, \( B^{(ex)} \) is the magnetic field produced by sources located beneath the photosphere and by currents in the solar-wind region, \( B^{(m)} \) is the field produced by inductive currents in the photosphere that prevents the penetration of the coronal-current field into the Sun, \( B^{(i)} \) is the field produced by the current flowing along the ring axis, \( g \) is the free-fall acceleration at the photospheric level, \( k \) is the dissipation coefficient, and \( v \) is the velocity.

We used the same parameters for the model as in Filippov et al. (2002) except for the mass of the filament per unit length. We chose \( 10^5 \, \text{g cm}^{-1} \), a more typical value for an average filament, because we do not need to fit the result to the final velocity of \( 500 \, \text{km s}^{-1} \). The global coronal field \( B^{(ex)} \) is represented by two spherical harmonics, dipole and octupole. These harmonics dominate in the global field in the epoch of solar activity minimum. Our event does not occur at the minimum, however; the level of activity in 2012 June was not very high as the monthly averaged sunspot number was about 60. Therefore, the global magnetic field configuration was not typical for the maximum. The harmonic coefficients were chosen in such a way that the magnetic field strength is \( B \approx 1 \, \text{G} \) in the corona near the filament, and there is a null line at the height of \( 0.2 \, R_\odot \) above the equator. In this field, a flux rope with a current of \( \approx 10^{11} \, \text{A} \) will be in equilibrium at a height of \( \approx 30 \, \text{Mm} \). Equilibrium is defined mainly by the components of the Lorenz force in Equations (1) and (2). The gravity force is about two orders of magnitude weaker than the electromagnetic forces acting on the filament. Gravity does not appreciably affect the equilibrium position in the lower corona. However, the filament mass is significant for the kinematics of eruption.

Each value of the current corresponds to two equilibrium points in this curve—one above and one below some critical point whose current \( I \) corresponds to a single solution of Equations (1) and (2) with zero left-hand terms. If the current exceeds the critical value, equilibrium cannot be achieved in the corona. The left panels of Figure 11 show the evolution of the flux rope without dissipation after the loss of equilibrium due to the increase of the electric current strength. The current strength...
is only increased a small amount (~2%) over the critical value. We see that the true flux-rope eruption started in the southern hemisphere and propagated into the northern hemisphere.

It was pointed out by Filippov et al. (2001) that there is a stable equilibrium position higher in the corona for the erupting flux rope, but the kinetic energy gained by the flux rope does not allow it to stop in the higher equilibrium position. However, if we add some dissipation $-kv$ to the right hand side of the equations of motion, as was done by Filippov et al. (2001) for testing of the initial equilibrium stability, the flux rope can lose its momentum and stop at some height (the right panels of Figure 11). We choose the value of $k$ as $2 \times 10^2 \text{ g s}^{-1}$ in order to stop the ascending motion of the flux rope at a height of $4 R_\odot$. At a speed of 300 km s$^{-1}$, it creates a drag force of $kv = 6 \times 10^9 \text{ dyne}$ per unit length or about an order of magnitude stronger than the gravitational force $fg = 7 \times 10^8 \text{ dyne}$ at a height of $2 R_\odot$.

Although we did not apply additional constraints in our models to fit the observational data, we can see that the kinematics shown in the right panels of Figure 11 are very similar to the observed kinematics presented in Figure 10. We compare the segments of curves between the dashed vertical lines in Figure 11(d) with the dotted blue line fit in Figure 10(a) and the segments of curves between the dashed vertical lines in Figure 11(e) with the black dotted line connecting the data points in Figure 10(b). They show six-hour intervals of the CME core evolution. Evidently, the curves are very similar and the quantities are close to each other. Comparison of Figure 8 with the calculated trajectory in Figure 11(f) also confirms the conclusion that the model rather adequately describes the observed event. However, the nature of the dissipation or the drag force is unclear to us. It is possibly aerodynamic drag or includes some additional dissipative mechanisms.
4. DISCUSSION AND CONCLUSIONS

We have presented a multi-wavelength analysis of the relationship of the whipping-like asymmetric filament eruption, the associated CME, and the outer coronal downflows in the form of the CME core on 2012 June 17 and 18. A summary of our results is as follows:

1. The observations show whipping-like, highly asymmetric filament eruption with an active (southeastern) leg and an anchored (northwestern) leg.
2. During the eruption, a two-ribbon flare occurred underneath the eastern part of the filament. This supports the standard flare model (CSHKP) of reconnection well.
3. The deceleration profile of the CME core shows that gravity is not the only force responsible for the downflow. The downflow of the CME core has been observed and may be due to the self consistent evolution of the flux rope in the coronal magnetic field.
4. Coronal ray deflection occurs during the upward motion of the CME. However, it does not exhibit a precise correlation with the coronal downflows.

Recently, Liu et al. (2009b) presented observations of two types of asymmetric filament eruptions, i.e., whipping- and zipping-like configurations. In the whipping-like eruptions, the active leg whips upward and the observed hard X-ray source locations shift toward the anchored leg. In the zipping-like asymmetric eruption, the active leg instead moves along the neutral line and the hard X-ray sources move away from the anchored leg. In our present observations, the filament eruption is whipping-like and highly asymmetric, however, without any significant propagation of flare brightening toward its anchored leg. Whipped filament also rises near its southern activated footpoint, and energy deposition in the form of flare ribbons occurs only beneath it. The asymmetric eruption of the filament later produced a slow CME that deflected the coronal ray in the outer corona. Thereafter, the coronal downflow was observed from \( \approx 4.33 R_\odot \) toward the Sun. Previously, Wang & Sheeley (2002) observed the CME core fallback from 1998–2001. They found that the fallback events occurred in impulsive but relatively slow CMEs. The fall of core material may be due to its interaction with the background plasma which removes momentum from the CME core. McKenzie & Hudson (1999) have reported unique observations of downward streaming plasma flow above the coronal supra arcades during the decay phase of a solar flare on 1999 January 20, and outlined its most likely cause to be the cross sections of evacuated flux tubes resulting from intermittent reconnection following the associated CME. However, in this case, we have a moderate CME beyond \( 2 R_\odot \) with its core, formed by a highly asymmetric filament eruption that may start downflowing due to its self-consistent evolution in the coronal magnetic field as shown in our model calculations (Figure 11).

In conclusion, our present multi-wavelength study shows a unique relationship between the asymmetric filament eruption, the flare as per the standard model, the associated CME, and the initiation of coronal downflows around \( \approx 4.33 R_\odot \). Studies such as this may elucidate the physical conditions of the outer corona and its coupling through various types of transients and plasma dynamics occurring in the lower solar atmosphere. New observations should be performed using future high-resolution observations from space and the ground to shed new light on such significant phenomena and their relationship in the solar atmosphere.

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REFERENCES

Asai, A., Yokoyama, T., Shimojo, M., & Shibata, K. 2004, ApJL, 605, L77
Benz, A. O. 2008, LRSP, 5, 1
Botha, G. J. J., Arber, T. D., & Srivastava, A. K. 2012, ApJ, 745, 53
Brueckner, G. E., Howard, R. A., Koomen, M. J., et al. 1995, SoPh, 162, 357
Carmichael, H. 1964, NASSP, 50, 451
Chandra, R., Pariat, E., Schmieder, B., Mandrini, C. H., & Uddin, W. 2010, SoPh, 261, 127
Chandra, R., Schmieder, B., Mandrini, C. H., et al. 2011, SoPh, 269, 83
Durrant, C. J. 2002, SoPh, 211, 83
Filippenkov, B., & Srivastava, A. K. 2010, SoPh, 266, 123
Filippenkov, B., & Srivastava, A. K. 2011, SoPh, 270, 151
Filippenkov, B. P., Gopalswamy, N., & Lozhechkin, A. V. 2001, SoPh, 203, 119
Filippov, B. P., Gopalswamy, N., & Lozhechkin, A. V. 2002, ARep, 46, 417
Hirayama, T. 1974, SoPh, 34, 323
Innes, D. E., McKenzie, D. E., & Wang, T. 2003, SoPh, 217, 247
Kopp, N. C., Uddin, W., Srivastava, A. K., et al. 2013, AdSpR, 52, 1
Kopp, R. A., & Pneuman, G. W. 1976, SoPh, 50, 85
Kumar, P., Srivastava, A. K., Filippenkov, B., Erdélyi, R., & Uddin, W. 2011, SoPh, 272, 301
Labrosse, N., Heinzel, P., Vial, J.-C., et al. 2010, SSRv, 151, 243
Lemen, J. R., Title, A. M., Akin, D. J., et al. 2012, SoPh, 275, 17
Lin, J., Forbes, T. G., Isenberg, P. A., & Demoulin, P. 1998, ApJ, 504, 1006
Liu, R., Alexander, D., & Gilbert, H. R. 2009a, ApJ, 691, 1079
Liu, Y., Su, J., Xu, Z., et al. 2009b, ApJL, 696, L70
Mackay, D. H., Karpen, J. T., Ballerese, I. L., Schmieder, B., & Aulanier, G. 2010, SSRv, 151, 333
McKenzie, D. E. 2000, SoPh, 195, 381
McKenzie, D. E., & Hudson, H. S. 1999, ApJL, 519, L93
Riley, P., Lionel, R., Mikić, Z., & Linker, J. 2008, ApJ, 672, 1221
Srivastava, A. K., Zaqarashvili, T. V., Kumar, P., & Khodachenko, M. L. 2010, ApJ, 715, 292
Sheeley, N. R., Jr., Knudson, T. N., & Wang, Y.-M. 2001, ApJL, 546, L131
Sheeley, N. R., Jr., & Wang, Y.-M. 2002, ApJL, 579, 874
Shibata, K. 1999, Ap&SS, 264, 129
Srivastava, A. K., Erdélyi, R., Tripathi, D., et al. 2013, ApJL, 765, L42
Srivastava, A. K., Zaqarashvili, T. V., Kumar, P., & Khodachenko, M. L. 2010, ApJL, 715, 292
Sterling, A. C., & Moore, R. L. 2005, ApJ, 630, 1148
Sturrock, P. A. 1966, Nature, 211, 695
Tripathi, D., Gibson, S. E., Qiu, J., et al. 2009, A&A, 498, 295
Tripathi, D., Isobe, H., & Mason, H. E. 2006a, A&A, 453, 1111
Tripathi, D., Solanki, S. K., Mason, H. E., & Webb, D. F. 2007, A&A, 472, 633
Tripathi, D., Solanki, S. K., Schwenn, R., et al. 2006b, A&A, 494, 369
Wang, Y.-M., Sheeley, N. R., Howard, R. A., & Sinnett, G. M. 1999, GeoRL, 26, 1203
Yang, J., Jiang, Y., Yang, B., et al. 2012, SoPh, 279, 115
Zhang, J., Cheng, X., & Ding, M.-D. 2012, NatCo, 3, 747